NASA Contractor Report 172521

Final Technical Report FY 1983/1984

Development of Powder Metallurgy 2XXX Series Al Alloy Plate and Sheet Materials for High Temperature Aircraft Structural Applications

D. J. Chellman

LOCKHEED – CALIFORNIA COMPANY
BURBANK, CALIFORNIA 91520

CONTRACT NO. NAS1-16048
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FOREWORD

This report documents the results of an on-going technical evaluation for the FY 1983/1984 time period performed by the Lockheed-California Company on advanced powder metallurgy Al alloy materials. The present technical effort involves the development and characterization of powder metallurgy 2XXX series Al alloy plate and sheet materials for high temperature aircraft structural applications. The reporting period is from 30 September 1982 to 30 September 1984. The research study was jointly conducted for the NASA Advanced Materials and Structures Branch and the NASA Advanced Supersonic Technology Project Office under NASA-LaRC Contract NAS1-16048, Modification 14. S.M. Dollyhigh and W.B. Lisagor, Jr. served as Technical Monitors on the present effort at the NASA-Langley Research Center.

The author is grateful to the extensive and thorough subcontract work performed by H.G. Paris, J.A. Walker, and their associates at the Technical Research Laboratory of Aluminum Company of America. The author is also grateful to G.G. Wald and I.F. Sakata for their technical contributions to this effort.

The author dedicates these research studies on PM 2XXX series Al alloys to the memory of G.G. Wald whose passing was marked on 10 September 1982. He formulated the metallurgical basis for all Lockheed research and development activities in the PM Al alloy development area and served continuously as a consulting metallurgist on the present effort. His technical brilliance, disarming wit, and endless enthusiasm will be greatly missed by all of his colleagues.

Prior work conducted during FY 1981/1982 (15 August 1981 through 30 September 1982) by the Lockheed-California Company on this contract is reported by NASA Contractor Report 172408, entitled "Development of Powder Metallurgy 2XXX Series Al Alloys for High Temperature Aircraft Structural Applications.

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D. J. Chellman, Lockheed-California Company

SUMMARY

The objective of the present investigation is to fabricate and evaluate PM 2124 Al alloy plate and sheet materials in accordance with NASA program goals for damage tolerance and fatigue resistance. Previous research has indicated the outstanding strength - toughness relationship available with PM 2124 Al - Zr modified alloy compositions in extruded product forms. The range of processing conditions was explored in the fabrication of plate and sheet gage materials, as well as the resultant mechanical and metallurgical properties. The PM composition based on Al-3.70 Cu-1.85 Mg - 0.20 Mn with 0.60 wt. pct. Zr was selected for investigation. Flat rolled material consisting of 0.250 in. thick plate and 0.070 in. thick sheet was fabricated using selected thermal mechanical treatments (TMT). The schedule of TMT operations was designed to yield the extreme conditions of grain structure normally encountered in the fabrication of flat rolled products, specifically recrystallized and unrecrystallized. The PM Al alloy plate and sheet materials exhibited improved strength properties at thin gages compared to IM Al alloys, as a consequence of their enhanced ability to inhibit recrystallization and grain growth. In addition, the PM 2124 Al alloys offer much better combinations of strength and toughness over equivalent IM Al. The alloy microstructures were examined by optical metallography and crystallographic texture techniques in order to establish the metallurgical basis for these significant property improvements.

SYMBOLS, ABBREVIATIONS, ACRONYMS

Symbol	Definition	Customary Engineering Units
AA	artificially aged	-
E_c	modulus of elasticity in compression	Msi
E, E_t	modulus of elasticity in tension	Msi
ε	engineering strain	in/in
$\bar{\varepsilon}$	effective extrusion strain	non-dim
$\dot{\varepsilon}$	time-average strain rate	in/in-sec
G.P. (B) Zones	pre-precipitation clusters of Cu atoms on Al cube planes	-

Symbol	Definition	Customary Engineering Units
Hi-Cu	high copper	-
Hi-Mn	high manganese	-
Hi-Zr	high zirconium	-
hr	hour	-
HM	high elastic modulus	-
HS	high strength	-
ΔK	stress intensity factor range	ksi-in$^{1/2}$
K_{app}	apparent plane stress fracture toughness	ksi-in$^{1/2}$
K_c	critical stress intensity factor	ksi-in$^{1/2}$
K_{SC}	stress concentration factor	-
NA	naturally aged	-
NTS	notched tensile strength	ksi
NTS/YS	notched tensile strength to yield strength ratio	non-dim
PA	artificially aged to peak strength condition	-
R	minimum to maximum fatigue stress factor	-
ρ	density	-
SEM	scanning electron microscopy	-
SHT, ST	solution heat treatment	-
σ	engineering stress	ksi
s, sec	seconds	-
S	Al_2CuMg intermetallic precipitate equilibrium phase	-
S'	Al/Cu/Mg transition phase	-
θ	Al_2Cu intermetallic precipitate equilibrium phase	-
θ'	Al/Cu transition phase	-
θ''	ordered 2nd step G.P. zone formation (G.P. II)	-
TEM	transmission electron microscopy	-

Symbol	Definition	Customary Engineering Units
TMT	thermomechanical treatment	-
WQ	water quench	-
w/o, wt. pct.	weight percent	-
YS	yield strength (0.2% offset)	ksi
UPE	unit propagation energy	in-lb/in

1. INTRODUCTION

1.1 Objectives

The general objective of the fiscal year (FY) 1983/1984 structures and materials technology studies is to identify and conduct the research and development activities necessary to support decisions related to plans for future United States aircraft transportation systems. A major portion of the technology studies are focused on the development and evaluation of advanced Al alloy materials. Since 1978 Lockheed-California Company has been involved in the development of a family of advanced Al alloys in conjunction with several Al alloy producers. The research efforts have been directed toward the identification, fabrication, and characterization of a family of powder metallurgy (PM) Al alloys tailored to satisfy specific design properties, including high strength, damage tolerance and fatigue resistance, high modulus, and low density. The goal is to realize Al alloys that exhibit specific strengths comparable to Ti alloys for supersonic cruise applications in the temperature range of 250° to 350°F. The technical approach has involved the implementation of alloying and processing methods that offer potential improvements in elevated temperature behavior over conventional Al alloys. New Al alloys are of interest for higher performance military and commercial aircraft systems because of their relatively low cost and ease of fabrication compared to alternative alloy materials.

The alloying and processing development work reported herein covers the FY 1983/1984 research efforts undertaken for achieving the damage tolerant and fatigue resistant target objectives given in Table 1. Research activities in coordination with the Aluminum Company of America (Alcoa) addressed the application of PM processing methods, alloy content modifications, and thermal mechanical treatments (TMT) within the 2XXX series Al alloy system. Ingot metallurgy (IM) alloy materials based on 2XXX series or Al-Cu-Mg-(Mn) alloys have been extensively used in naturally aged (NA) tempers for damage tolerant and fatigue resistant structural applications at room temperature. However, the necessity of elevated temperature service dictates the employment of artificially aged (AA) tempers where the strength, fracture toughness, and notched fatigue property combination available with IM Al alloys is relatively poor. Alloy development studies on three previous NASA-LaRC contracts have demonstrated that significant improvements in strength, fracture toughness, and notched fatigue properties are obtained by the fabrication of 2XXX series Al alloys with PM processing techniques. The prior research on PM 2XXX Al alloys involved the evaluation of Al-Cu-X and Al-Cu-Mg-X alloy compositions in the form of rectangular extruded bar. The PM Al-Cu-Mg-Zr alloy system exhibited the most attractive combination of properties for damage tolerant and fatigue resistant structural requirements. Since a major usage of 2XXX series Al alloys for damage tolerant structural applications involves the product forms of plate and sheet, it is important to establish the processing methods leading to PM 2XXX Al alloy flat rolled plate and sheet material forms. The technical objectives of the present study address this issue in terms of: (1) exploring

TABLE 1. - ADVANCED ALUMINUM ALLOY TARGET OBJECTIVES - DAMAGE TOLERANT AND FATIGUE RESISTANT

Requirements	Damage Tolerance
1. Strength: F_{tu} – ksi	68
F_{cy} – ksi	62
2. Fatigue: $^*F_{MAX}$ – ksi	30
$^{**}\Delta K$ – ksi $\sqrt{in.}$	7.2
3. Fracture Toughness: K_{APP} – ksi $\sqrt{in.}$	81
K_{IC} – ksi $\sqrt{in.}$	30
4. Density: lb/in^3	–
5. Elastic Modulus: Msi	10.7
6. Corrosion Resistance:	
Stress Corrosion – ksi	25
Exfoliation corrosion	>EA
Fatigue and Crack Growth Goals:	
$^*F_{MAX}$ at 10^5 Cycles,	
$K_t = 3$, $R = 0.1$	
$^{**}\Delta K$ for $R = 0.1$, $DA/DN = 10^{-6}$ in/in, Rel. Humid. >95%	

Notes: Elevated temperature property goals include
a) Stability - room temperature properties unaffected by exposure up to 350^0F
b) Greater than 80 percent of room temperature properties in range of 250^0 to 350^0F

the range of potential microstructural variations encountered in the fabrication of flat rolled materials, and (2) establishing the relationships between deformation processing conditions, alloy microstructure, and mechanical property behavior. The research efforts on PM 2XXX Al alloy plate and sheet materials in this reporting period included the following activities:

- Preparation of two PM 2124 Al alloy type billet slabs suitable for rolling studies based on Zr content modifications
- Fabrication of two processing variants in 0.250 in. gage plate involving selected hot and warm rolling schedules
- Fabrication of two processing variants in 0.070 in. gage sheet involving selected hot and warm rolling schedules
- Determination of solution heat treatment, stretch, and age hardening behavior of candidate PM 2124 Al alloy plate and sheet materials by hardness and tensile screening tests
- Assessment of influence of Zr additions on subgrain and grain structure, recrystallization, and texture of PM Al alloy plate and sheet
- Establish strength-fracture toughness property combinations available with candidate PM 2124 Al alloy plate and sheet materials
- Evaluation of the microstructural features of slab, billet, plate, and sheet material forms by optical metallographic and crystallographic texture techniques
- Comparison of candidate PM 2124 Al alloy plate and sheet materials with respect to achievement of damage tolerant and fatigue resistant objectives

1.2 Background

The achievement of improved property combinations for Al alloys applicable to supersonic aircraft structures has been demonstrated on three previous NASA-LaRC research programs by employing alloy modifications and PM processing. For damage tolerant and fatigue resistant goals (Table 1), an attractive combination of tensile strength, fracture toughness, and notched fatigue properties was displayed by PM composition variations based on 2124, 2618, and 2219 type Al alloys. In particular, research activities in cooperation with Alcoa have demonstrated the outstanding strength - toughness relationship available with extruded PM 2124 series Al alloys involving Zr content additions. The following results were obtained and discussed in the previous studies with respect to attainment of the damage tolerant and fatigue resistant target objectives: (1) high strength levels were obtained for the PM 2124

Al-Zr modified alloy extrusions, (2) outstanding fracture toughness values were shown for artificially aged tempers in the PM 2XXX Al alloys, (3) notched fatigue strengths generally exceeded the property values associated with IM 2XXX Al alloys, and (4) elevated temperature resistance and stability properties for the PM 2XXX series Al alloy extrusions were achieved up to approximately 350°F. The property behavior in comparison to IM Al alloys suggest that complex composition and processing relationships exist between precipitate and dispersoid strengthening, elevated temperature environments, and fracture toughness considerations.

The PM Al-Cu-Mg-Zr alloys based on the 2124 type Al alloy composition have demonstrated the most promising property combinations with respect to attainment of the damage tolerant and fatigue resistant goals. Alloy development studies have indicated that Zr additions are particularly effective in contributing to a fine grained and unrecrystallized microstructure in Al alloy extrusions. The PM composition consisting of Al-3.70 Cu-1.85 Mg-0.20 Mn with 0.60 wt. pct. Zr addition exhibited the most favorable combination of properties based on the previous investigations. The rapid solidification rates produced by atomization were observed to prohibit the precipitation of coarse, primary Al_3Zr phases in this alloy system. A major portion of the Zr precipitated as finely distributed, coherent Al_3Zr phases during vacuum preheating and solution heat treatment. The proper balance between Cu and Mg contents eliminated undissolved, soluble constituents such as Al_2CuMg and Al_2Cu during atomization. The resultant extruded microstructures produced a unique combination of strength, fracture toughness, and notched fatigue resistance. An increase in the volume fraction of coherent Al_3Zr, unlike incoherent $Al_{20}Cu_2Mn_3$ dispersoids, appears to strengthen the PM Al base alloy by either dislocation-precipitate interactions or retardation of recrystallization mechanisms. Furthermore, coherent Al_3Zr does not appear to degrade fracture toughness to the extent that incoherent $Al_{20}Cu_2Mn_3$ does. Consequently, the addition of 0.60 wt. pct. Zr to the base alloy, incorporated with a 935°F solution heat treatment temperature, produces a PM Al alloy that exceeds all tensile property, fracture toughness, and notched fatigue goals for damage tolerant and fatigue resistant applications in the artificially aged condition. The PM 2124 Al-Zr modified alloys displayed superior mechanical properties when compared to both other PM 2124 Al alloys and an experimental IM 2124 composition with 0.12 wt. pct. Zr.

The introduction and structural application of PM 2XXX series Al alloys on aircraft systems is currently limited by the lack of established processing methods for flat rolled product forms. Rolled plate and sheet materials comprise a major portion of the product forms utilized for damage tolerant and fatigue resistant design applications. For this reason, the primary objectives of the present study are to explore the range of processing conditions and to determine the resultant mechanical and metallurgical properties of PM 2124 Al plate and sheet materials. The optimum PM 2124 Al-Zr modified alloy composition identified in recent alloy development studies has been employed to provide a baseline for property and microstructure comparisons. Flat rolled material consisting of 0.250 in. thick plate and 0.070 in. thick sheet has been fabricated using selected thermal mechanical treatments (TMT). The schedule of TMT operations has been designed to yield the extreme conditions of grain structure normally encountered in the fabrication of flat rolled

products, specifically recrystallized and unrecrystallized. The present study addresses the relationships between processing conditions, mechanical property behavior, and alloy microstructures for these PM Al flat rolled materials.

2. EXPERIMENTAL PROCEDURE

2.1 Material Selection

The PM 2124 Al type alloy composition for the flat rolled materials was selected on the basis of alloy development studies conducted on previous NASA-LaRC contracts. The Al-Cu-Mg-Zr alloy content including 0.60 wt. pct. Zr additions was designed to eliminate undissolved soluble constituents and incoherent dispersoids. The equilibrium solvus diagram was used to select the maximum Cu and Mg content consistent with full dissolution at the ternary eutectic temperature of 946°F. Literature references suggest that a balance of Cu and Mg alloying contents in the ratio of 2.2/1.0 are known to yield stoichiometric Al_2CuMg or S phases. The melt composition was adjusted based on experience to account for Mg losses to oxidation during atomization, and for Cu and Mg losses to formation of Al_7Cu_2Fe and Mg_2Si insoluble phases. Precipitation of the incoherent dispersoid, $Al_{20}Cu_2Mn_3$, was avoided by maintaining the Mn content lower than the solid solubility limit (approximately 0.12 wt. pct.) at the vacuum preheat and solution heat treatment temperatures. The intermetallic compound Al_3Zr replaces $Al_{20}Cu_2Mn_3$ as the primary dispersoid phase. A Zr solute level of 0.60 wt. pct. was selected to determine the effect of exceeding the equilibrium solubility limit by a factor of five on the relative amounts of coherent, cubic Al_3Zr phases. The interaction of hot working conditions and the role of Al_3Zr phases in influencing the control of alloy microstructures was evaluated with respect to program objectives. The target and actual melt compositions of the PM Al-Cu-Mg-Zr alloy, designated 514163, are listed in Table 2 along with the alloy compositions investigated in previous NASA-LaRC funded research activities. The Cu/Mg ratio indicates that the actual powder chemistries are close to the required value for precipitation hardened Al_2CuMg (S phase) alloy systems. Compositions for the primary dispersoid forming element, namely Zr, are judged to be within acceptable limits. An IM 2124 Al alloy containing Zr additions, designated 503315, was included from a prior study to facilitate a direct comparison of the IM and PM processing on properties and microstructures.

The hot working strategy for the PM 2124 Al-Zr modified alloy involves a modification of the basic 2024 Al composition to allow for addition of substantial amounts of Zr to maintain selected grain structures. The use of rapid solidification processing with powder metallurgy methods ensures that the relatively large volume fraction of Al_3Zr phases are fine and uniformly distributed in the alloy microstructure. Recent work in this area has indicated that the rapid cooling rates produce very fine dendrite arm spacings,

TABLE 2. - PM 2124 Al ALLOY COMPOSITIONS

Program Phase	Sample No.		Alloy Content (wt. pct.)								
			Cu	Mg	Si	Fe	Ni	Mn	Zr	Zn	Cr
I	513707	Target	3.80	1.80	0.15	1.50	1.50	–	–	–	–
		Actual	3.80	1.93	0.07	1.53	1.73	0.01	–	–	–
I	513708	Target	4.00	1.60	–	–	–	1.50	–	–	–
		Actual	3.93	1.57	–	0.06	0.01	1.50	–	–	–
I	513709	Target	4.00	1.60	–	–	–	0.50	–	–	–
		Actual	4.06	1.62	–	0.05	–	0.51	–	–	–
II	513887	Target	5.50	0.35	–	–	–	0.30	–	–	–
		Actual	5.19	0.38	0.12	0.06	–	0.18	–	–	–
II	513888	Target	3.50	1.65	0.20	1.20	1.10	–	–	–	–
		Actual	3.32	1.67	0.06	1.03	0.93	0.01	–	–	–
II	513889	Target	3.50	1.65	0.20	–	–	–	–	–	–
		Actual	3.19	1.67	0.24	0.07	–	0.01	–	–	–
III	514041	Target	3.70	1.85	–	–	–	0.20	0.14	0.10	0.10
		Actual	3.73	1.81	0.02	0.04	0.01	0.14	0.12	0.08	0.01
III	514042	Target	3.70	1.95	–	–	–	0.20	0.70	0.10	0.10
		Actual	3.67	1.84	0.03	0.03	0.04	0.16	0.60	0.10	0.01
III	503315	Target	4.30	1.50	–	–	–	0.90	0.12	–	–
		Actual	4.36	1.56	0.07	0.06	0.00	0.90	0.10	0.01	0.00
IV	514163	Target	3.70	1.95	–	–	–	0.20	0.70	0.10	0.10
		Actual	3.68	1.85	0.03	0.03	0.04	0.17	0.60	0.07	0.02

and finer constituent particles and inclusions that do not reduce the fracture toughness as do coarser distributions. The role of Al_3Zr in promoting a fine grain, unrecrystallized grain structure with superior mechanical property behavior has been substantiated in PM 2124Al-Zr modified extruded materials. Thermal mechanical treatments on high strength Al alloys have been extensively studied using controlled rolling practices where the objective is to change the grain structure, size, and shape. The TMT variables usually consist of solution heat treatment, preaging, deformation, and final aging. In terms of the present effort, these findings form a basis for obtaining systematic variations in the properties and microstructures of PM 2124 Al flat rolled materials. Rolling slab temperatures and reduction schedules have been explored in order to obtain 0.250 in. thick plate and 0.070 in. thick sheet with the required degree of recrystallization, texture, and grain size.

2.2 Material and Specimen Preparation

The PM 2124 Al-Zr modified alloy composition (514163) used in this flat rolled material study was fabricated from one lot of gas atomized powder. Approximately 300 pounds of irregularly shaped powder was produced at the Alcoa Technical Center for conversion into consolidated billets. The atomization and consolidation schemes used to fabricate the PM billets were identical to those employed in previous investigations. Stock material for preparation of flat rolled plate and sheet materials was obtained by isothermal forging of the consolidated billets. A complete description of the PM processing steps is given in this section. Figure 1 shows the actual size distribution from two samples of the atomized powder and the average particle diameter (A.P.D.) determined by a Fisher subsieve size analyzer. Approximately 50 percent of the weight distribution of the powders was below 20-25 µm. These atomized powder characteristics and solidification rates are typical of powder lots used in previous PM 2XXX Al alloy studies.

2.2.1 Atomization and consolidation.- A description of the pertinent powder characteristics, consolidation, and billet fabrication conditions used to produce the PM 2124 Al-Zr modified alloy under evaluation in the current study are listed in Table 3. A 400 pound pot of the required melt composition was air atomized to recover at least 300 pounds of fine, irregular shaped powder with at least 85 percent by weight smaller than -325 mesh. The powder was screened through a 100 mesh sieve prior to cold isostatic pressing. Two 110 pound cold compacts of the alloy composition, 7.4 in. dia. by 42.9 in. long, were formed in a wet bag system by isostatically pressing the powder at 30 ksi to approximately 75 percent of the theoretical alloy density. The compacts were transferred into a 3003 Al canister, sealed, and vacuum preheated for approximately 1 hour at 20-40 µm pressure. Differential scanning calorimetry was used to identify the solvus and solidus temperatures. The recommended consolidation conditions were similar to those employed in the previous study involving PM 2124 Al-Zr modified alloy extrusions. Consequently, the hot pressing temperature of 935°F was chosen from these results and the Al-Cu-Mg phase diagram to avoid equilibrium melting at the ternary eutectic of 946°F. Proper selection of the vacuum preheat and hot pressing temperatures ensures both effective degassing and homogenization of the billet compact. The total heat-up cycle for hot pressing took approximately seven to eight hours to complete. After the evacuation lines were sealed, the compacts were removed from the furnace and hot pressed at 90 ksi to full density. The hot pressed PM billet is 28.2 in. long from 8.4 in. dia. at the top, to 9.2 in. dia. at the bottom, in order to facilitate billet ejection from the hot pressing cylinder. The can material was removed by scalping the billet to 6.0 in. dia. and cutting 1.0 in. from each end. Two 6.0 in. dia. by 26.0 in. long PM billet charges were subsequently available for isothermal forging into rolling slabs.

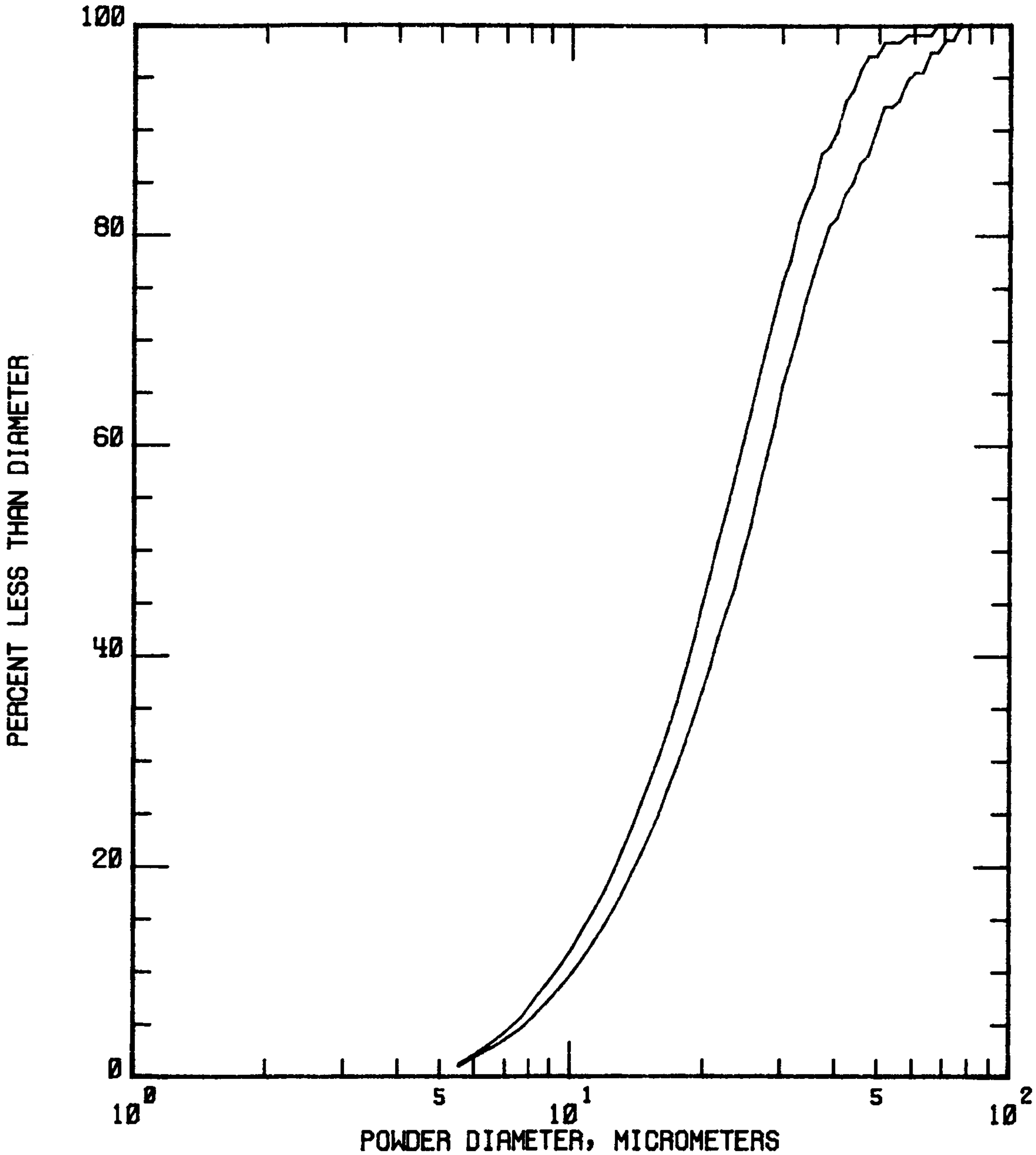


Figure 1. - Atomized powder size distribution.

TABLE 3. - POWDER CHARACTERISTICS, CONSOLIDATION, AND BILLET FABRICATION CONDITIONS

Sample No.	Powders A.P.D., μm	Billets (1) Vacuum Preheat (2) Temperature, (^{o}F)	Extrusion, Plate, and Sheet (3)		
			Actual (4) Temperature, (^{o}F)	Solution Treatment Temperature, (^{o}F)	Stress (5) Relief %
514041-1	13.5	947	657	935	2.0
-2		947	634	935	2.0
-3		965	641	935	2.0
-4		965	640	935	2.0
514042-1	13.3	947	666	935	2.0
-2		947	666	935	2.0
-3		965	670	935	2.0
-4		965	667	935	2.0
503315-1	NA (6)	935 (1)	740	935	2.0
-2	NA (6)	935 (1)	745	935	2.0
514163-1	13.5	965	–	935	2.0
-2		965	–	935	2.0

Notes: (1) Ingot pre-heated in air furnace.

(2) Actual compaction temperature is approximately 30^{o}F lower.

(3) A constant ram speed of 1.3 in./min. and butt length of 1.5 in. were used for all alloys.

(4) Temperature measured at rear of extrusion after butt was sheared off.

(5) Target Value.

(6) Not Applicable - Ingot.

2.2.2 Plate and sheet rolling.- Rolling stock for 0.250 in. thick plate and 0.070 in. thick sheet materials was produced by directly forging the two 110 lb. PM billets into 2.0 in. slabs on open dies. One PM billet, designated 514163-1, was soaked for four hours at 800°F and forged to final thickness in a 30 minute time span, with a finishing surface temperature of 600°F. The other billet, designated 514163-2, was forged at a faster strain rate in about 15 minutes. The latter slab also had a 40 minute longer soak in the holding furnace, and its starting temperature had dropped to 770°F due to opening the furnace from the previous billet. The finishing temperature was measured at 590°F. The only difference in visual appearance of the two slabs was that the 514163-1 slab had "wavy sides" along its length, while the latter slab was reasonably straight. The final dimensions of both slabs was 2.0 in. thickness by 11.0 in. width by 36.0 in. length. The 514163-1 slab was cut into four equal sized pieces for the initial rolling activity (approximately 2.0 in. thickness by 5.0 in. width by 18.0 in. length), and labeled as 514163-1A, -1B, -1C, and -1D. The remaining 514163-2 slab was held as back-up material to supplement the current work.

The plate rolling strategy was designed to provide two variants representative of the extreme differences encountered in rolled plate microstructures, namely: (1) schedule A - fully recrystallized grain structure with a random texture, and (2) schedule B - unrecrystallized grain structure similar to PM 2124 Al extrusions with a thick recrystallized surface layer. The PM forged slabs, 514163-1A and 514163-1B, were rolled according to the following schedules to obtain the required mecrostructures. The 514163-1A slab was preaged at 750°F for 12 hours and air cooled to room temperature. Subsequently, it was re-heated to 550°F and warm rolled to 0.250 in. thickness. At 0.600 in. thickness the temperature of the rolling slab had dropped to about 450°F, and severe edge cracking was encountered in the rear 20.0 in. of the 46.0 in. piece. The rolled plate was cut to 26.0 in. and re-heated to 515°F, with warm rolling continued to completion. The finishing temperature at 0.250 in. thickness was approximately 430°F. A total of seven rolling passes were used to fabricate the plates in accordance with schedule A. The 514163-1B slab was heated to 920°F and soaked for approximately 1.75 hours. It was removed from the furnace and allowed to cool to approximately 875°F, where it was subsequently hot rolled to 0.237 in. thickness in five passes. The rolling slab was reheated at 0.600 in. thickness when the slab temperature had fallen to about 750°F. The rolling conditions are consistent with fabrication of plates according to schedule B.

The strategy for sheet rolling was developed to produce similar differences in sheet microstructures (schedules A and B) by warm and hot rolling practices. The third section of the original rolling slab, 514163-1C, was hot rolled to 1.0 in. thickness by the same practices used on slab 514163-1B. The 1.0 in. PM slab was subsequently cooled to room temperature, and cut into two equally sized slabs for preparation of sheet materials. The 514163-CC slab was warm rolled to sheet gage thicknesses. It was initially re-heated to 750°F and soaked for 12 hr. The slab was then reheated to 550°F and warm rolled to 0.070 in. thickness. In a similar manner, the 514163-CH slab was hot rolled to sheet gage thicknesses. The slab was reheated to 875°F and hot rolled to 0.070 in. thickness using large reductions per pass.

2.2.3 Heat treatment.- The flat rolled plate and sheet materials received the same solution heat treatment practice as employed in the extruded bar, hold at a temperature of 935°F for one hour, followed by an immediate quench in cold water. Both plate and sheet forms were stretched in the range of 1.75-2.25 percent immediately after quenching to ensure stress relief. An aging study was performed on the two variants involving warm and hot rolled plate. Small samples of the plates were prepared, and Vickers hardening response as a function of aging time were obtained for aging temperatures between 325° and 425°F.

2.2.4 Microstructural examination.- Metallographic specimens for optical microscopy, x-ray analysis, and transmission electron microscopy (TEM) were cut from the mid-length of the rolled plates at the T/2, W/4 locations.

Standard polishing procedures and Keller's reagent were used to reveal the grain and sub-grain structures. Transmission x-ray pinhole Laue patterns and pole figures were employed to identify intermetallic phases. TEM was used to provide structural information on the microstructural features that were unresolved by optical metallography and to identify the crystal structure, morphology, and size of Al_3Zr phases.

Crystallographic texture measurements were obtained from chemically thinned wafers representing the LT orientation. Intensity measurements from (111) diffraction were continuously collected between 0 and 60 degrees inclination to the specimen normal in 5 degree increments, with the sample rotated over 360 degrees by 2 degree steps. The raw data were automatically corrected by a computer subroutine for adsorption before comparison to the intensity of a randomly textured Al standard. Pole figures were automatically plotted using intensity contours at 0.75, 1.25, 2.0, 3.0, and 4.0 times random. The maximum intensity within the pole figure is obtained by dividing any random intensity by the corresponding percentage provided on the plot.

Information on the crystallographic structure of the Al_3Zr phases was determined by selected area diffraction (SAD) and aperture limited microdiffraction. The compound Al_3Zr is known to exist in either the cubic $L1_2$ or tetragonal DO_{23} structure. The cubic $L1_2$ structure is coherent with the matrix and is identified by the presence of superlattice spots in the SAD patterns. The tetragonal, incoherent DO_{23} structure is identified by obtaining two microdiffraction patterns with different zone axes. The angle between the zone axes was determined from the specimen stage rotation and tilt by measurement of the resultant angle on a Wolff net. The d spacings and interplanar angles for the tetragonal Al_3Zr phase were calculated using a standard computer program, and the appropriate a_o and c_o values.

2.2.5 Mechanical testing details.- The mechanical testing objective of the current investigation is to determine the peak artificial aging practice for the PM 2124 Al-Zr modified alloy plate and sheet materials. Fracture toughness indications for these PM Al alloy products were also determined in the natural and peak aged tempers, and compared to IM 2124 Al alloy properties. The tensile and toughness specimens were machined in accordance with ASTM standards. Tensile properties were obtained for the plate and sheet materials in both the longitudinal and transverse directions. Standard plate and sheet type specimens were used according to practices established at the Alcoa Technical Center. A measure of fracture toughness for the plate materials in the L-T and T-L orientations as a function of aging time was obtained using the precracked Charpy test specimen. The toughness numbers were calculated by the empirical formula.

$$K = \left[E * (W/A)/2 * (1-\mu) \right]^{\frac{1}{2}}$$

according to practices found to be suitable for Al alloy products. These Charpy toughness data were used primarily as an inexpensive screening tool. Values of Charpy toughness in excess of about 25 to 30 ksi in.$^{1/2}$ significantly overestimate true plane strain facture toughness values. The rectangular cross section of the Charpy specimen is normally 0.394 inch square. Due to the smaller flat rolled material gage, the thickness dimension of the specimen was reduced to 0.235 in. The specimen span was maintained at 1.55 in. Duplicate specimens were used in most of the plate material tests. The toughness of the sheet materials as a function of aging time was evaluated in the L-T and T-L orientations using the Kahn tear test specimen. Analysis of the test results provide two indications of fracture resistance for sheet materials, namely tear strength and unit propagation energy. Duplicate specimens were also used in most of the sheet material tests.

3. RESULTS AND ANALYSIS

3.1 Hardness Study

An isothermal aging study was conducted on both the warm rolled and hot rolled conditions of the 0.250 in. plate. Age hardening response was determined by following Vickers hardness as a function of time at aging temperatures between 325° and 425°F, with 25°F increments. Times were selected between 0.5 and 100 hours in order to identify the kinetics of precipitation reactions. The average data are presented in Table 4 with typical graphical representations of the response curves in Figures 2 and 3. Both PM plate conditions displayed similar aging responses over the time-temperature ranges examined. The hot rolled plate shows a consistent age hardening response, with peak hardness levels occurring at 350° and 375°F. In comparison, the aging behavior of the warm rolled plate is more ambiguous, since a maximum hardness was observed only at 375°F. The 350°F aging response was not as strong as observed in the hot rolled plate variant. Maximum hardness was observed to occur at both 350° and 375°F for approximately 16 hours and 4 hours, respectively. At temperatures of 375°F and below, the hardening response of the warm rolled condition lagged that of the hot rolled plate. For aging times after peak hardening at 350° and 375°F, the warm rolled processing variant maintained a higher hardness level than the hot rolled condition. The age hardening study demonstrated that peak strength tempers can be obtained for the two rolling variants at either 350° or 375°F within reasonable aging times. On the basis of the aging results it was decided that the two temperatures of 350° and 375°F would be used to evaluate the strength - toughness relationships in the PM 2124 Al plate materials. Age hardening was also observed to occur at 325°F to the approximate levels obtained for the higher temperatures, but with significantly longer aging times.

TABLE 4. - VICKERS HARDNESS DATA ON ROLLED PLATE VARIANTS

Hot Rolled Condition (514163-1), V_H^o = 144					
Aging Time (hr.)	Aging Temperature (^oF)				
	325	350	375	400	425
0.5	142	140	133	138	143
1	144	142	141	141	132
2	149	140	151	144	130
4	144	145	148	140	129
8	148	143	140	135	119
12	142	140	141	124	115
16	147	144	128	127	111
32	149	143	123	118	100
100	140	131	116	106	90
Warm Rolled Condition (514163-1), V_H^o = 142					
	325	350	375	400	425
0.5	134	127	125	127	148
1	133	133	128	142	144
2	135	141	141	147	140
4	137	141	151	141	134
8	131	137	147	131	126
12	143	151	146	131	111
16	144	154	142	131	114
32	150	148	134	116	99
100	150	141	119	100	94

Note: Vickers Hardness Number with 5 gram Applied Load, Average of Three Readings

3.2 Tensile Properties

The initial rolling experiments on the PM 2124 Al-Zr modified alloy were effective in fabricating plate and sheet materials representative of schedules A and B. Aging studies were conducted on the warm and hot rolled conditions of both the 0.250 in. plate and 0.070 in. sheet. The age hardening behavior was determined by a combination of Vickers hardness, tensile testing, and toughness indications for the aging temperatures of 350° and 375°F. Times were selected between 1 and 32 hours based on the results of the hardness survey. The tensile properties obtained for the PM plate and sheet variants are given in the following two sub-sections.

3.2.1 Tensile properties of plate variants.- The two processing variants involving 0.250 in. thick plate were evaluated on the basis of tensile properties. Tensile testing was performed in the longitudinal (L) and transverse (T) directions as a function of isothermal aging at 350° and 375°F. The

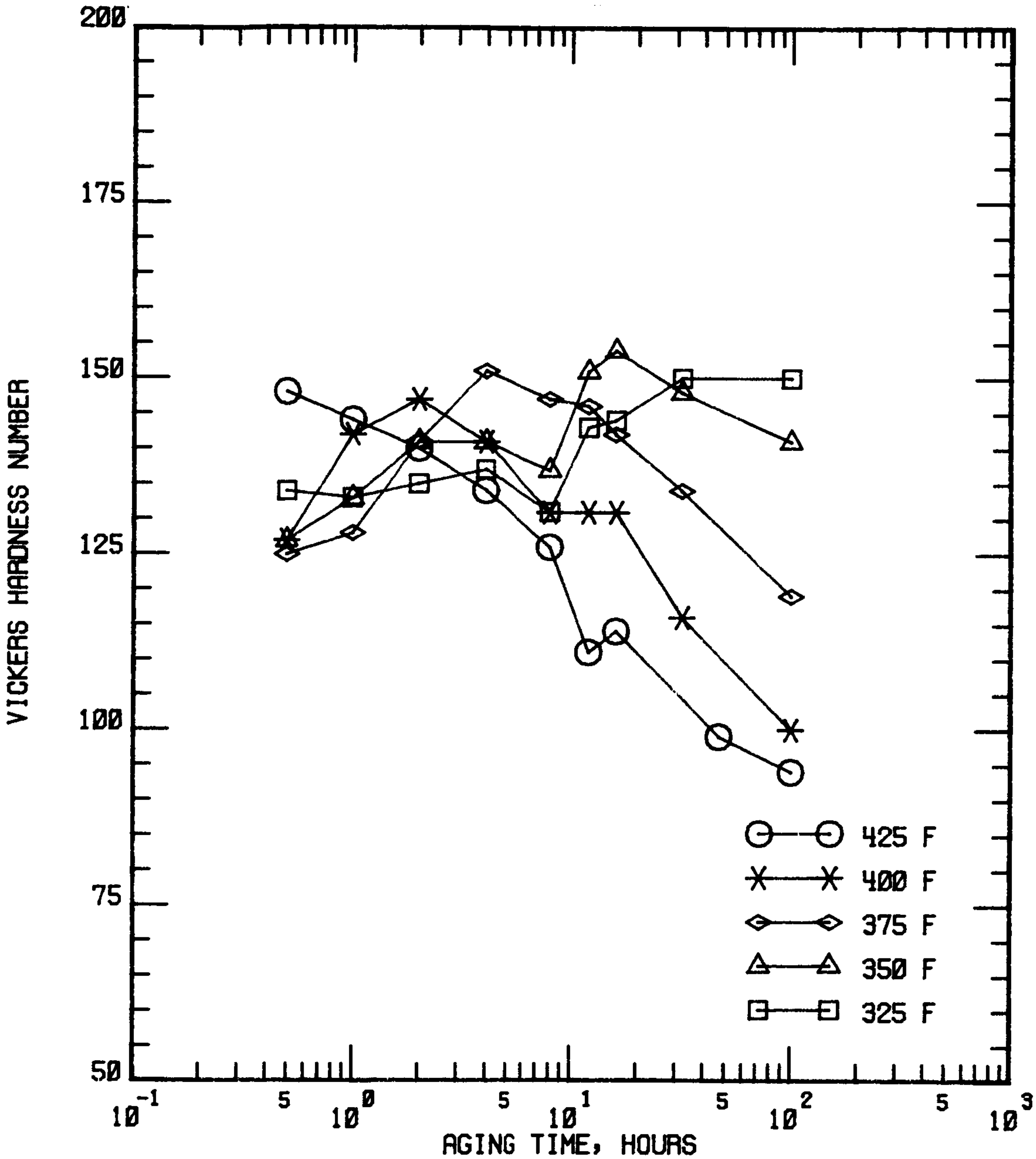


Figure 2. - Hardness response of hot rolled plate.

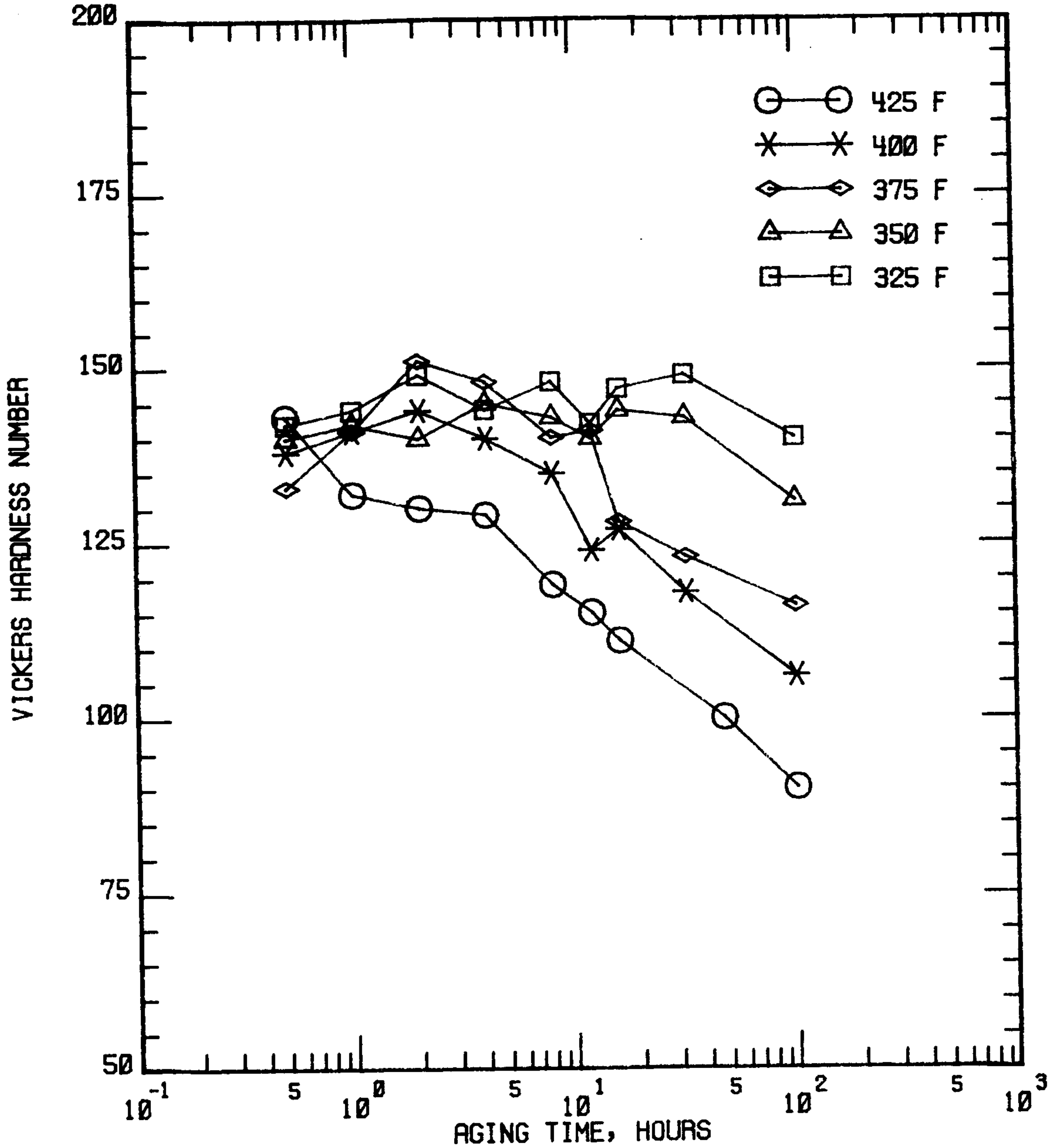


Figure 3. - Hardness response of warm rolled plate.

tensile properties consisting of yield strength, tensile strength, and elongation are given in Tables 5 and 6 for the warm rolled plate and hot rolled plate variants, respectively. Figure 4 shows the longitudinal yield strength of the two PM plate conditions as a function of aging at 350° and 375°F, while Figure 5 displays a similar plot for tensile strength results. Both processing variants exhibited similar aging behavior over the time-temperature range examined, particularly with respect to yield strength levels. Peak yield strengths at 350° and 375°F were reached after 16 and 4 hours, respectively, for both processing variants. The yield strength peak at the lower temperature is quite broad, extending from approximately 12 to 32 hours. It is observed that equivalent longitudinal peak strengths are obtained on aging at the two temperatures, however the hot rolled plate material consistently developed the highest peak aged yield strength properties. The hot rolled processing variant had a peak yield strength of 65.4 ksi on aging at 350°F, while that of the warm rolled processing condition was 63.5 ksi. These tensile results generally agree with the aging response trends observed in the hardness study. With the exception of the hot rolled plate aged at 375°F, the tensile strength levels monotonically decreased on isothermal aging at both temperatures. Tensile strengths were essentially identical between the hot rolled and warm rolled processing variants at 350°F, with values of 69.9 and 69.7 ksi, respectively. Thus, there were no significant differences in peak aged tensile strength properties as a function of either processing variant or aging temperature. Figures 6 and 7 show the age hardening behavior of the two processing conditions at each aging temperature in the transverse direction. In contrast to the previous results, the warm rolled plate variant exhibited higher yield and tensile strength properties than the hot rolled processing condition on aging at 350° and 375°F. The transverse tensile strengths were observed to undergo a steady decline with aging time, as noted with the longitudinal tensile properties. It appears that the lower aging temperature of 350°F offers a slightly better aging response with respect to transverse tensile property behavior.

3.2.2 Tensile properties of sheet variants.- The two processing variants involving 0.070 in. thick sheet were evaluated in a similar manner to the plate materials for tensile property behavior. Tensile testing was conducted in the longitudinal (L) and transverse (T) directions as a function of isothermal aging at 350° and 375°F. The tensile properties consisting of yield strength, tensile strength, and elongation are given in Tables 7 and 8 for the warm rolled sheet and hot rolled sheet materials, respectively. Figure 8 shows the longitudinal yield stength of the two PM sheet conditions as a function of aging at 350° and 375°F, while Figure 9 displays a similar plot for tensile strength results. The PM sheet variants exhibited a markedly similar behavior on aging to that observed for the rolled plate materials. Peak strength of both processing variants was reached at the same aging time as the plate, approximately 16 hours at 350°F, however, the strength levels appear to develop slightly more slowly from the initial naturally aged temper than in the plate. The results of aging the hot rolled variant at 375°F

TABLE 5a. - TENSILE PROPERTIES OF 0.250 IN. THICK WARM ROLLED PLATE

Warm Rolled Plate (514163-1B), Aged at 350°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
Longitudinal			
0 hours*	(61.9)	(74.6)	16
	(58.8)	(71.6)	16
average	(60.4)	(73.1)	16
4	(57.8)	(69.2)	17
8*	(61.3)	(68.7)	16
	(61.2)	(68.9)	15
average	(61.3)	(68.8)	16
16 (peak)*	(66.0)	(70.3)	15
	(64.8)	(69.1)	14
average	(65.4)	(69.7)	15
32*	(63.8)	(69.4)	15
	(62.1)	(68.4)	14
average	(63.0)	(68.9)	15
Long transverse			
0 hours*	(53.5)	(70.2)	18
	(52.5)	(69.6)	21
average	(53.0)	(69.9)	20
4	(54.6)	(68.1)	15
8	(58.0)	(67.7)	18
16*	(63.5)	(68.5)	15
	(62.8)	(67.9)	15
average	(63.2)	(68.2)	15
32	(62.0)	(67.4)	14

*Duplicate Tests

TABLE 5b. - TENSILE PROPERTIES OF 0.250 IN. THICK WARM ROLLED PLATE

Warm Rolled Plate (514163-1B), Aged at 375°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
Longitudinal			
1	(57.0)	(68.6)	17
2*	(58.9)	(67.7)	16
	(59.7)	(68.7)	16
average	(59.3)	(68.2)	16
4 (peak)*	(65.8)	(70.6)	14
	(64.2)	(68.9)	14
average	(65.0)	(69.8)	14
8 (peak)	(65.4)	(70.3)	14
16	(60.7)	(67.9)	14

*Duplicate Tests

TABLE 5b. - TENSILE PROPERTIES OF 0.250 IN. THICK WARM ROLLED PLATE (Continued)

Warm Rolled Plate (514163-1B), Aged at 375°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
Long transverse			
1 hour	(53.4)	(67.3)	22
2*	(56.1)	(66.6)	18
	(56.6)	(67.2)	20
average	(56.4)	(66.9)	19
4*	(63.2)	(68.6)	15
	(60.2)	(67.3)	16
average	(61.7)	(68.0)	16
8	(62.6)	(66.3)	15
16	(59.8)	(66.3)	14

*Duplicate Tests

showed a slower response also, reaching a longitudinal peak strength after 8 hours aging time. The hot rolled processing variant exhibited a better kinetic response with less over-aging at 350°F, but both processing conditions resulted in approximately the same peak strength levels. A 2.0 - 3.0 ksi strength improvement is obtained by peak aging at the lower temperature of 350°F in both PM sheet processing variants. The hot rolled sheet material also produced a better tensile strength response, as noted in Figure 9. Figures 10 and 11 show the age hardening behavior in the transverse direction for the two sheet processing conditions at each aging temperature. The transverse yield strength still shows a hardening contribution after the longest aging time of 32 hours at the lower temperature of 350°F. The hot rolled sheet variant exhibited higher transverse yield and tensile strength levels by up to 6.0 ksi when compared to the warm rolled condition. Both transverse yield and tensile strengths showed essentially equivalent peak aged levels for the two different aging temperatures. It is further observed that the rolled sheet variants displayed a distinctly lower naturally aged strength, thereby emphasizing the increased precipitation hardening associated with the PM sheet materials. Contrary to observations on the plate materials, the sheet variants showed significant hardening contributions in both yield and tensile strength levels on isothermal aging. It is also noted that the transverse yield and tensile strengths of the sheet variants exceed those obtained for the longitudinal direction. These differences in hardening response and orientation are probably due to variations in the grain structure of the rolled plate and sheet materials.

TABLE 6a. - TENSILE PROPERTIES OF 0.250 IN. THICK HOT ROLLED PLATE

Hot Rolled Plate (514163-1A), Aged at 350°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
Longitudinal			
0 hours*	(61.2)	(74.3)	17
	(58.5)	(70.7)	17
average	(59.9)	(72.5)	17
4	(60.1)	(71.7)	17
8	(62.5)	(70.9)	14
	(61.6)	(70.2)	13
average	(62.5)	(70.6)	14
16 (peak)*	(62.5)	(68.7)	12
	(63.9)	(70.5)	12
average	(63.5)	(69.9)	12
32	(62.7)	(69.1)	13
	(62.7)	(68.9)	12
average	(62.7)	(69.0)	13
Long transverse			
0 hours*	(57.4)	(72.1)	20
	(57.3)	(71.8)	19
average	(57.4)	(72.0)	20
4	(58.5)	(69.2)	19
8	(60.9)	(68.6)	16
16*	(64.3)	(68.3)	13
	(64.6)	(68.4)	13
average	(64.5)	(68.4)	13
32	(61.6)	(66.4)	12

*Duplicate Tests

TABLE 6b. - TENSILE PROPERTIES OF 0.250 IN. THICK HOT ROLLED PLATE

Hot Rolled Plate (514163-1A), Aged at 375°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
1*	(58.2)	(71.1)	18
	(59.4)	(72.1)	17
average	(58.8)	(71.6)	18
2*	(61.7)	(71.4)	15
	(59.9)	(70.1)	16
average	(60.8)	(70.8)	16
4 (peak)*	(62.5)	(69.4)	11
	(63.6)	(69.9)	13
average	(63.0)	(69.6)	12
8*	(62.8)	(69.1)	12
	(62.2)	(68.6)	12
average	(62.5)	(68.8)	12

*Duplicate Tests

TABLE 6b. - TENSILE PROPERTIES OF 0.250 IN. THICK HOT ROLLED PLATE (Continued)

Hot Rolled Plate (514163-1A), Aged at 375°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
Long transverse			
1	(58.2)	(69.3)	20
2*	(59.5)	(68.4)	19
	(59.8)	(68.2)	18
average	(59.6)	(68.3)	19
4*	(63.7)	(68.3)	14
	(62.7)	(68.1)	14
average	(63.2)	(68.2)	14
8	(63.1)	(67.5)	14
16	(60.3)	(66.6)	14

*Duplicate Tests

The PM Al-Cu-Mg-Zr alloy composition that displayed outstanding tensile strength and fracture toughness properties in extrusions also contributed to promising property combinations in the flat rolled product forms of plate and sheet. The benefits from PM processing are related to improvements in the control of alloy microstructures and possibly from a contribution to dispersion hardening through use of Zr solute additions. An increase in the hardening response of the plate and sheet materials is tentatively attributed to changes in the subgrain and grain structures. The highly unrecrystallized extrusions examined in an earlier phase of this program exhibited at best a flat age hardening response. This behavior probably occurred since the S' phase is heterogeneously precipitated, and thus the high density of dislocations in the vicinity of subgrain and grain boundaries offerred competing nucleation sites to the free dislocation density introduced by stress relief. In the case of flat rolled materials, particularly sheet gages, substantial recrystallization was obtained by the combination of TMT practices. The recrystallized microstructures led to lower naturally aged strengths for the PM materials, but reduced the amount of ineffective S' phase precipitation on subgrain and grain boundaries. Therefore, a larger volume fraction of S' phase was available for strengthening on artificial aging. The high strength levels in the peak aged sheet is a marked improvement over ingot metallurgy alloys. Recrystallization in thin product gages usually lead to significantly lower strength levels. In the PM 2124 Al-Zr modified sheet, the yield strength is approximately 10.0 ksi higher than the yield strength of IM 2034 in a comparable gage, the closest ingot metallurgy composition. In fact, the yield strength of the PM Al alloy exceeds equivalent gages of the IM Al alloy up to very thick sections where a highly unrecrystallized structure is known to be present. The transverse tensile properties of the PM flat rolled variants also exhibited high strength levels. In the hot rolled sheet materials, the transverse strengths were observed to exceed the longitudinal properties for both aging temperatures.

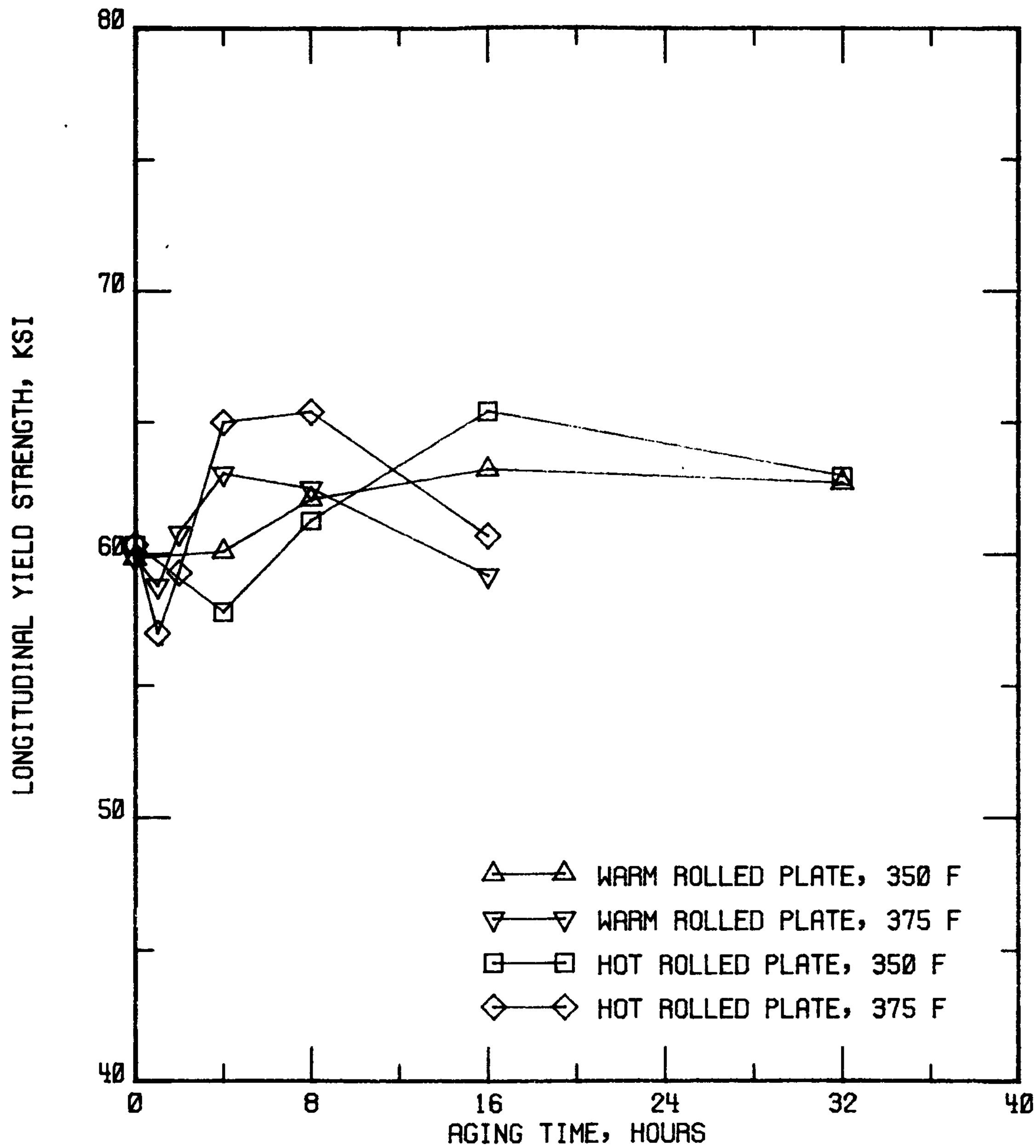


Figure 4. - Longitudinal yield strength of two PM plate variants as a function of aging at 350° and 375°F.

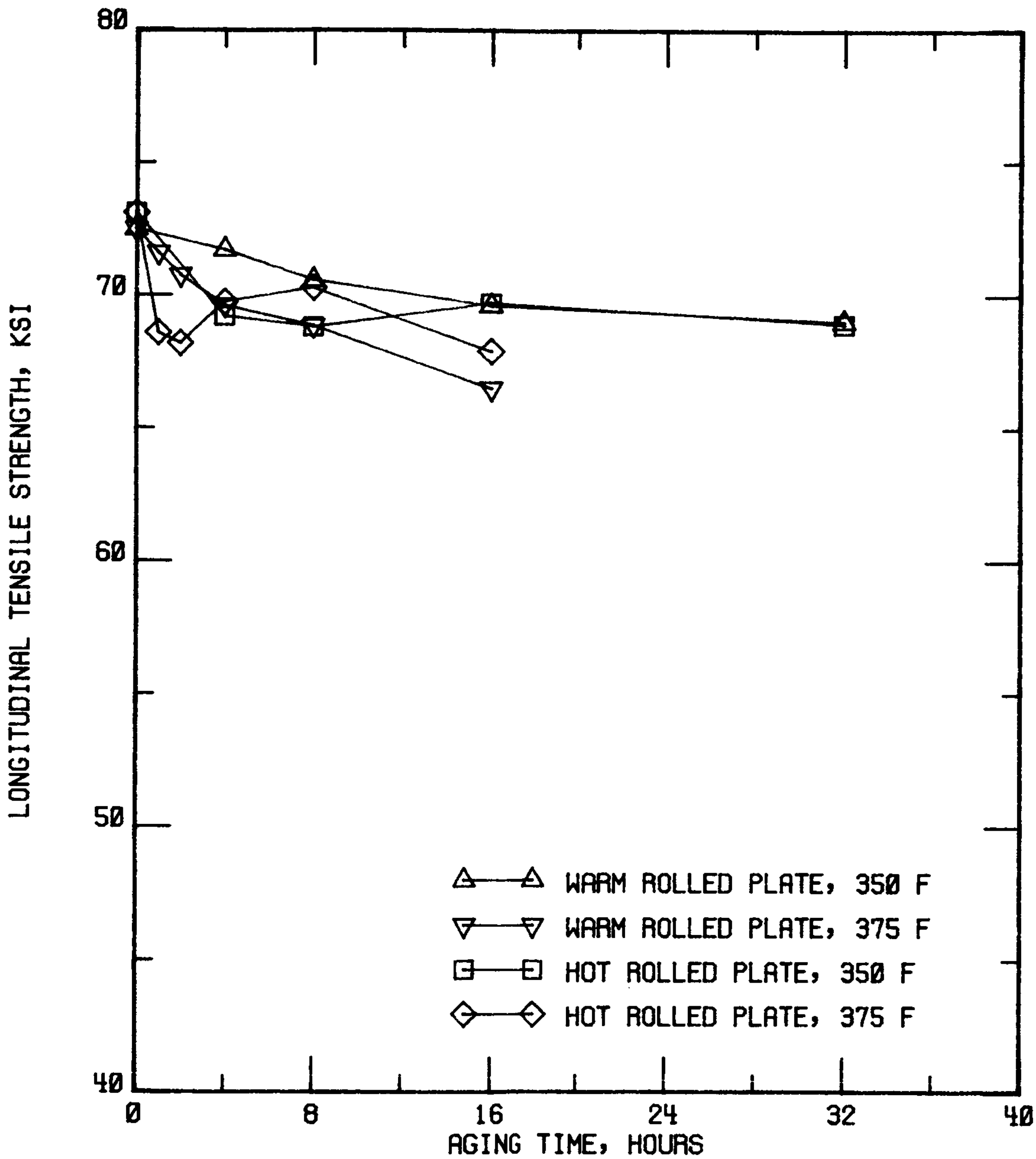


Figure 5. - Longitudinal tensile strength of two PM plate variants as a function of aging at 350° and 375°F.

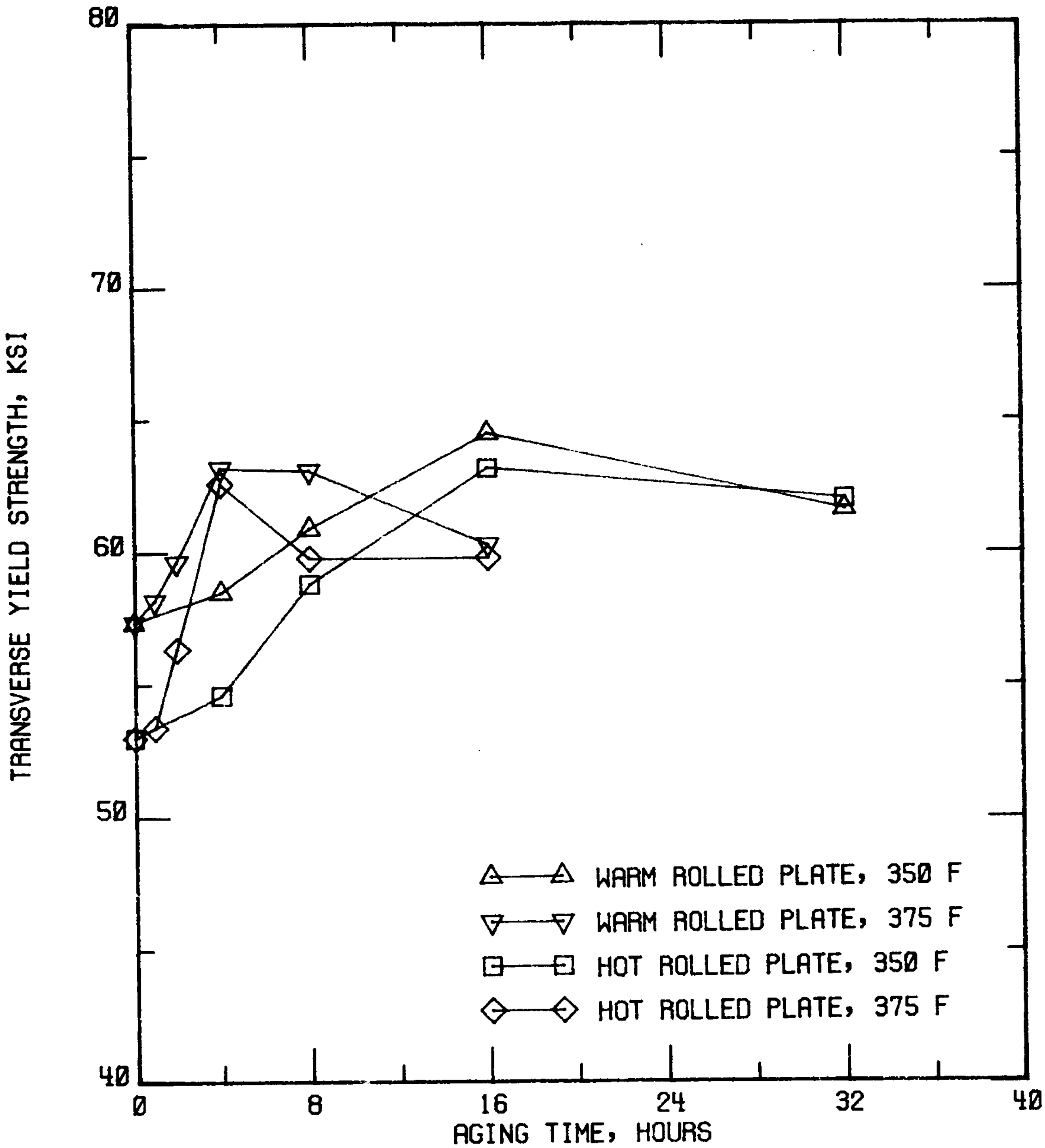


Figure 6. - Transverse yield strength of two PM plate variants as a function of aging at 350° and 375°F.

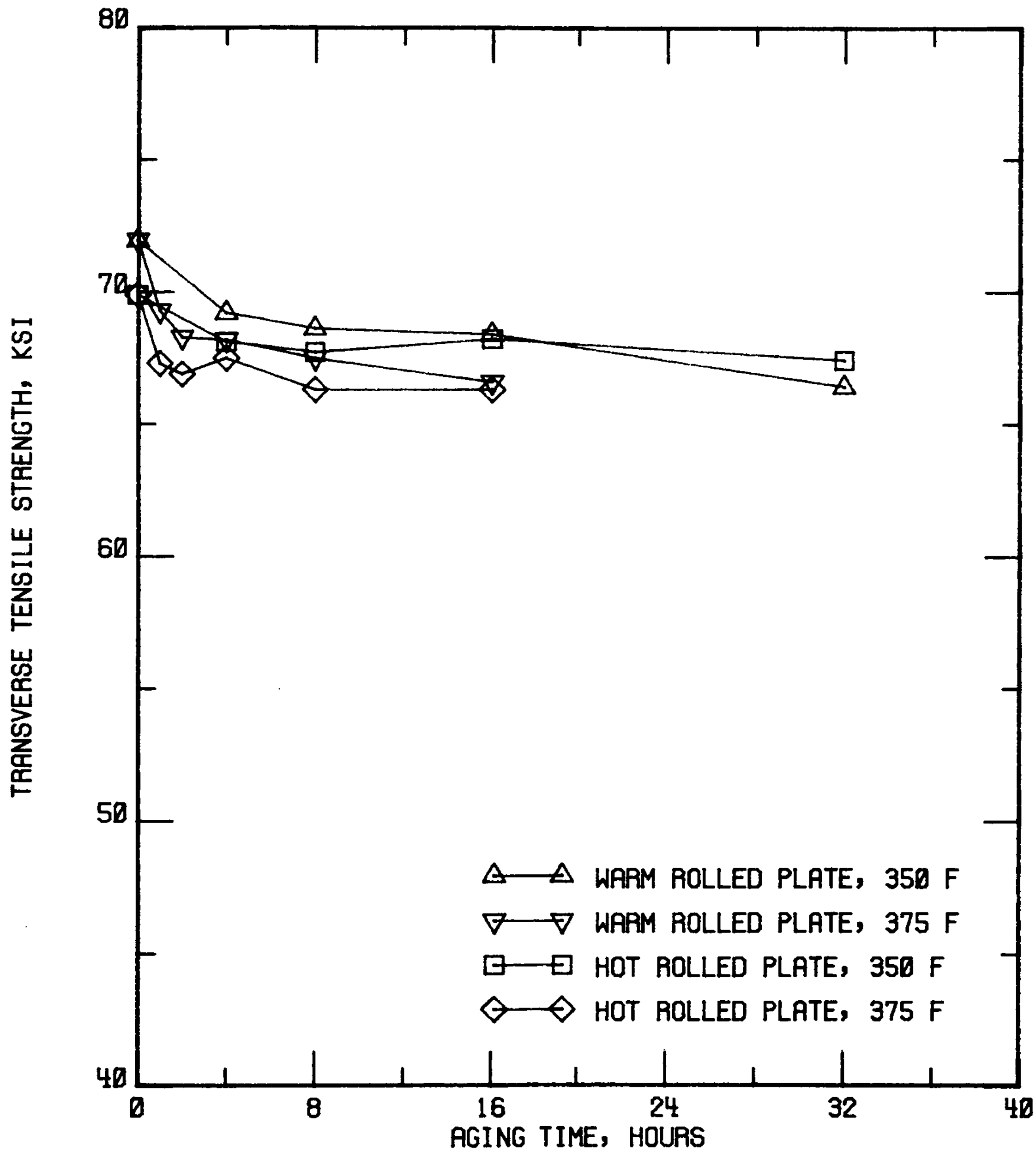


Figure 7. - Transverse tensile strength of two PM plate variants as a function of aging at 350° and 375°F.

TABLE 7a. - TENSILE PROPERTIES OF 0.070 IN. THICK WARM ROLLED SHEET

Warm Rolled Sheet (514163-CC), Aged at 350°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
Longitudinal			
0 hours*	(55.4)	(68.4)	18
	(56.2)	(69.2)	18
average	(55.8)	(68.8)	18
4	(54.8)	(67.7)	18
8	(55.0)	(66.9)	15
16*	(62.6)	(68.7)	10
	(65.6)	(69.5)	9
average	(64.1)	(69.1)	10
32	(61.0)	(66.9)	10
Long transverse			
0 hours*	(44.2)	(68.6)	16
	(44.2)	(68.3)	18
average	(44.2)	(68.5)	17
4*	(42.1)	(62.1)	18
	(42.2)	(62.6)	18
average	(42.2)	(62.4)	18
8	(46.5)	(63.3)	16
16*	(57.1)	(66.5)	11
	(57.1)	(66.8)	12
average	(57.1)	(66.7)	12
32	(60.5)	(67.1)	18

*Duplicate Tests

TABLE 7b. - TENSILE PROPERTIES OF 0.070 IN. THICK WARM ROLLED SHEET

Warm Rolled Sheet (514163-CC), Aged at 375°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
Longitudinal			
1	(48.1)	(66.1)	22
2*	(52.4)	(65.4)	17
	(51.8)	(66.7)	20
average	(52.1)	(66.0)	19
4*	(65.2)	(69.5)	10
	(60.2)	(67.2)	13
average	(62.6)	(68.4)	12
8	(64.0)	(69.1)	10

*Duplicate Tests

TABLE 7b. - TENSILE PROPERTIES OF 0.070 IN. THICK WARM ROLLED SHEET (Continued)

Warm Rolled Sheet (514163-CC), Aged at 375°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
Long transverse			
1	(42.7)	(66.6)	18
2*	(46.5)	(65.8)	17
	(45.6)	(66.1)	17
average	(46.0)	(66.0)	17
4*	(54.6)	(66.3)	11
	(54.5)	(66.3)	12
average	(54.6)	(66.3)	12
8	(59.4)	(66.4)	10
16	(58.1)	(66.1)	9

*Duplicate Tests

3.3 Fracture Toughness Properties

The tensile property evaluation on the PM 2124 Al-Zr modified alloy materials were effective in establishing the overall strength behavior as a function of aging treatment and product form. An indication of the fracture toughness properties for the PM Al plate and sheet materials was obtained by precracked Charpy and Kahn tear tests, respectively. The flat rolled products and aging time-temperature combinations were identical to those used in the tensile property study. The fracture toughness indications for the PM plate and sheet variants are given in the following two subsections.

3.3.1 Fracture toughness properties of plate variants.- The two processing variants involving 0.250 in. thick plate were evaluated with respect to fracture toughness resistance. Toughness testing was conducted in both the L-T and T-L orientations as a function of isothermal aging at 350° and 375°F. Data were converted from the Charpy test results to fracture toughness units by using an empirical method developed at Alcoa. The fracture toughness properties are given in Tables 9 and 10 for the warm rolled plate and hot rolled plate variants, respectively. Figure 12 shows the Charpy toughness versus yield strength relationship for the two PM plate materials in the L-T orientation, while Figure 13 displays a similar plot for the T-L orientation. A number of items are of particular significance in these figures. The data displayed relatively scattered values with no clear strength-toughness trend relationship being evident. The rolled plate products aged at 375°F showed the most scatter. The warm rolled plate aged at the lower temperature and the hot rolled plate aged at the higher temperature exhibited the better strength - toughness combinations. Inspection of Figure 12 also shows that the poorest combination of strength and toughness was obtained in both processing variants using the higher aging temperature of 375°F. Charpy data in the T-L orientation suggest that the warm rolled plate

TABLE 8a. - TENSILE PROPERTIES OF 0.070 IN. THICK HOT ROLLED SHEET

Hot Rolled Sheet (514163-CH), Aged at 350°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
Longitudinal			
0 hours*	(51.6)	(65.8)	20
	(51.6)	(65.4)	16
average	(51.6)	(65.6)	18
4	(55.2)	(67.1)	9
8	(54.9)	(65.3)	15
16*	(66.0)	(68.7)	10
	(63.5)	(67.9)	10
average	(64.8)	(68.3)	10
32	(64.8)	(69.3)	9
Long transverse			
0 hours*	(43.6)	(66.8)	18
	(44.3)	(67.7)	16
average	(44.0)	(67.2)	17
4	(52.4)	(69.3)	15
8	(58.9)	(69.6)	12
16*	(65.8)	(71.1)	9
	(64.8)	(70.0)	8
average	(65.3)	(70.6)	9
32	(63.8)	(69.6)	8

*Duplicate Tests

TABLE 8b. - TENSILE PROPERTIES OF 0.070 IN. THICK HOT ROLLED SHEET

Hot Rolled Sheet (514163-CH), Aged at 375°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
Longitudinal			
1	(51.4)	(64.0)	18
2*	(52.2)	(64.0)	17
	(55.4)	(64.9)	14
average	(53.8)	(64.4)	17
4*	(59.7)	(65.1)	12
	(59.1)	(65.6)	13
average	(59.4)	(65.4)	13
8	(61.2)	(66.0)	10
16	(58.1)	(66.1)	9

*Duplicate Tests

TABLE 8b. - TENSILE PROPERTIES OF 0.070 IN. THICK HOT ROLLED SHEET (Continued)

Hot Rolled Sheet (514163-CH) Aged at 375°F

Aging History	F_{ty} (ksi)	F_{tu} (ksi)	e (pct.)
Long transverse			
1	(49.4)	(67.5)	16
2*	(54.1)	(69.4)	16
	(48.8)	(66.2)	16
average	(51.4)	(67.8)	16
4*	(63.1)	(69.9)	9
	(62.6)	(69.5)	10
average	(62.8)	(69.7)	10
8	(63.8)	(69.8)	9
16	(61.3)	(68.8)	9

*Duplicate Tests

aged at either temperature was decidedly better than that of the hot rolled variant. Additional testing and analysis is required to make a categorical decision of the optimum processing condition for PM Al plate products. By way of comparison with conventional Al alloys, the best combination of strength and toughness in the PM Al plate materials is representative of approximately 65.0 ksi yield strength and 80.0 ksi-in$^{1/2}$ toughness values, respectively. A precracked Charpy estimate of the L-T fracture toughness of IM 2124 Al-T851 plate corresponds to about 30.0 ksi-in$^{1/2}$, at a yield strength of 66.0 ksi. Although the 2124 Al data are taken from thicker plate than that of the PM Al alloys, it is a significant indication of the magnitude of improvement in fracture toughness and strength achieved through PM processing methods.

3.3.2 Fracture toughness properties of sheet variants.- The two processing variants involving 0.070 in. thick sheet were evaluated with respect to fracture toughness resistance. Toughness testing was performed in both the L-T and T-L orientations as a function of isothermal aging at 350°F. An index of the fracture toughness of the PM Al sheet materials was assessed by two measures, the tear strength/yield strength ratio and the unit propagation energy (UPE). The fracture toughness properties are given in Tables 11 and 12 for the warm rolled sheet and hot rolled sheet variants, respectively. Figure 14 shows the tear strength/yield strength ratio versus yield strength data for the two PM Al sheet materials in the L-T orientation, while Figure 15 displays a similar plot for the T-L orientation. The L-T toughness results obey a common trend relationship, with the line in this figure representing a least squares fit to the data. It is noted that only the hot rolled sheet variant exhibited scatter with respect to the linear behavior. The T-L orientation results in Figure 15 showed a more consistent trend than observed with the L-T data. The strength - toughness combination of the two PM processing

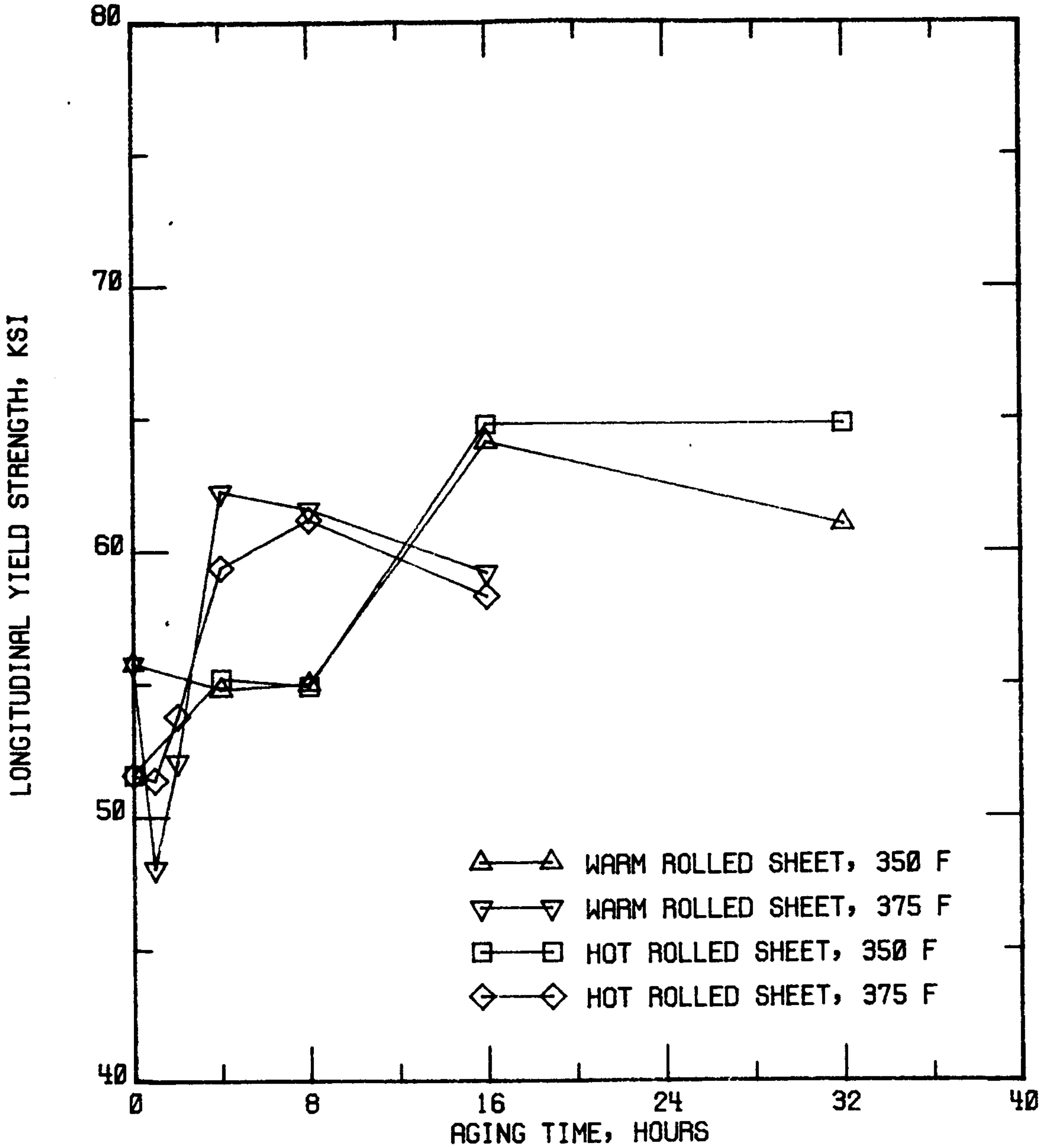


Figure 8. - Longitudinal yield strength of two PM sheet variants as a function of aging at 350° and 375°F.

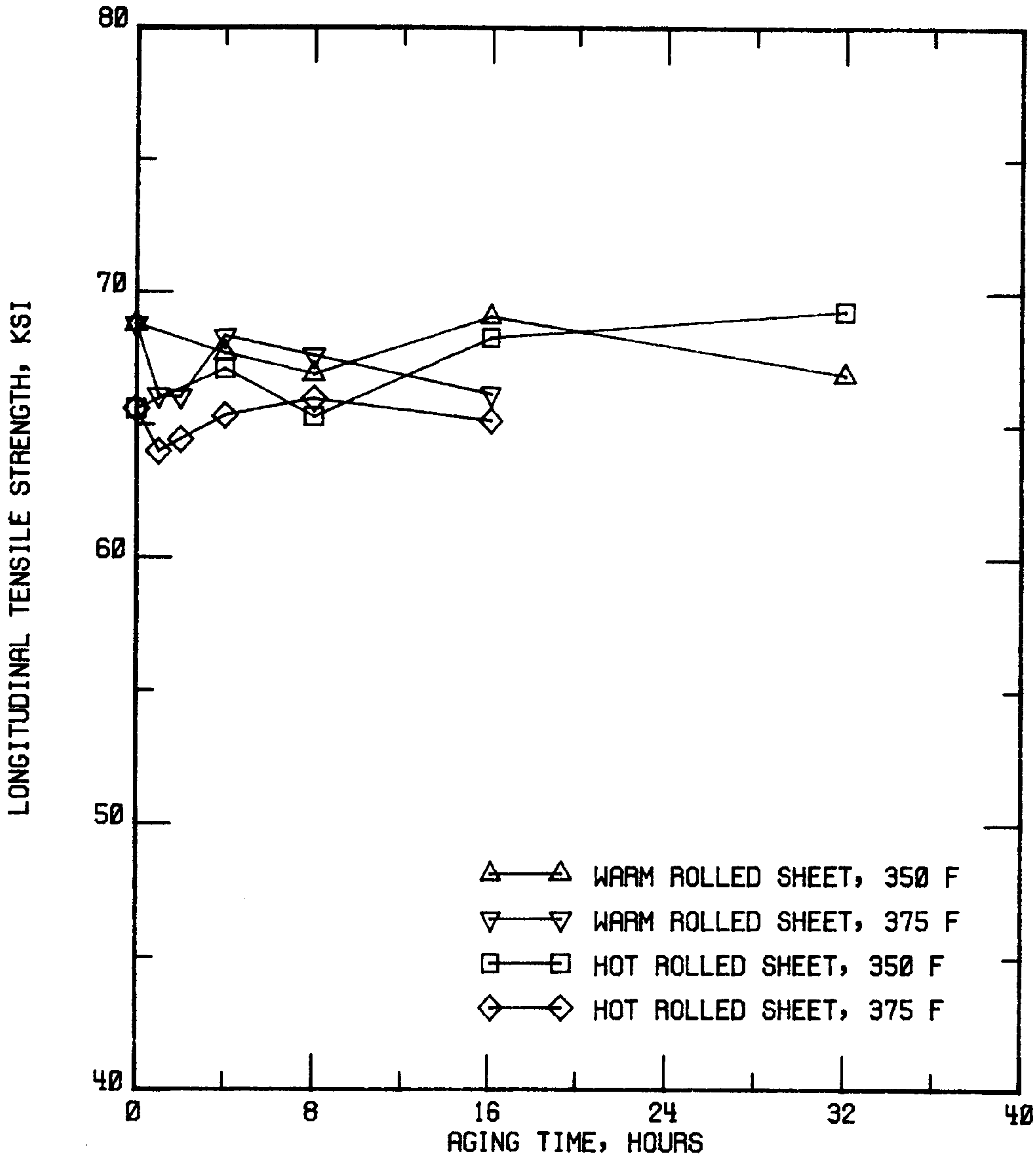


Figure 9. - Longitudinal tensile strength of two PM sheet variants as a function of aging at 350° and 375°F.

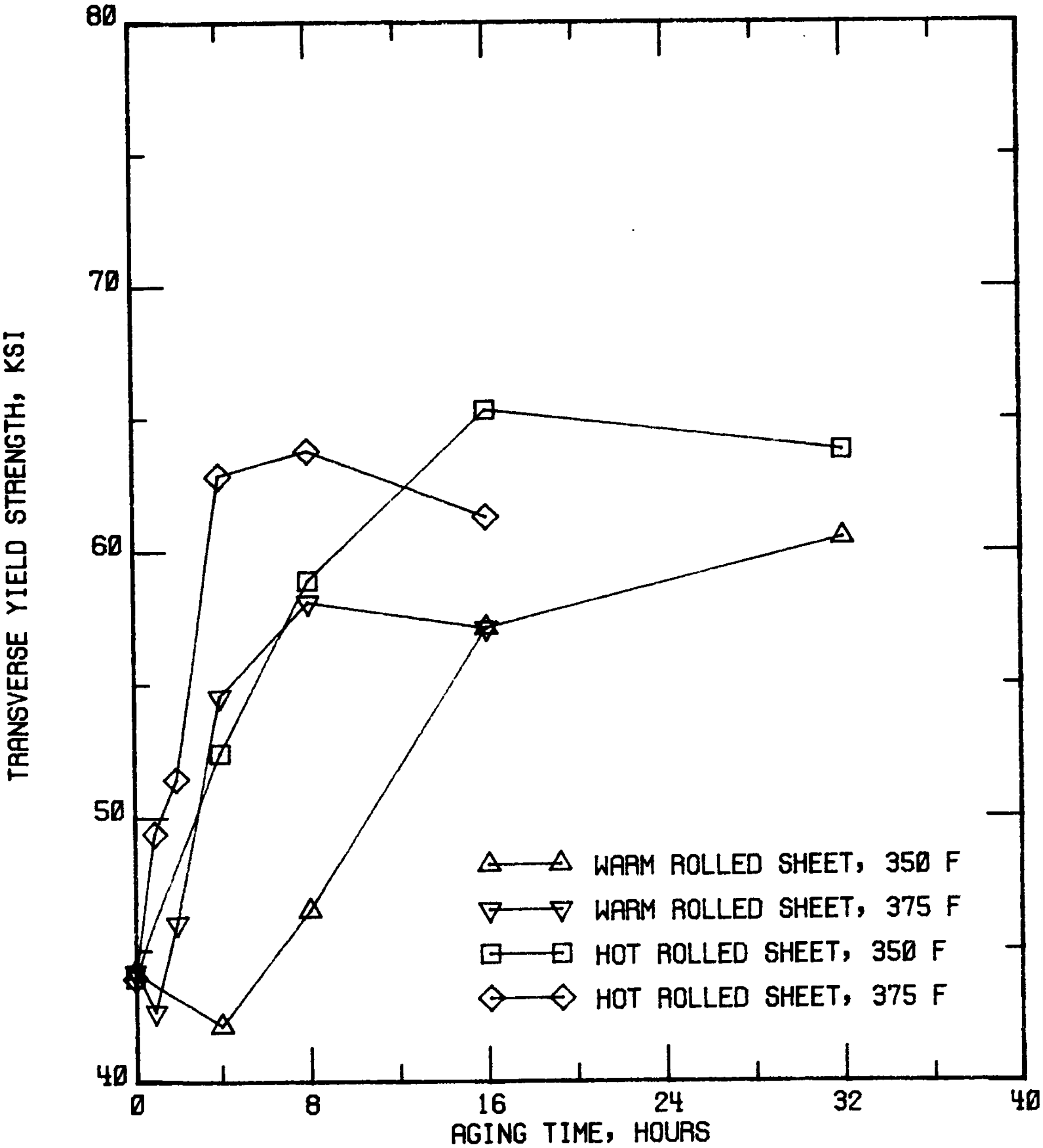


Figure 10. - Transverse yield strength of two PM sheet variants as a function of aging at 350° and 375°F.

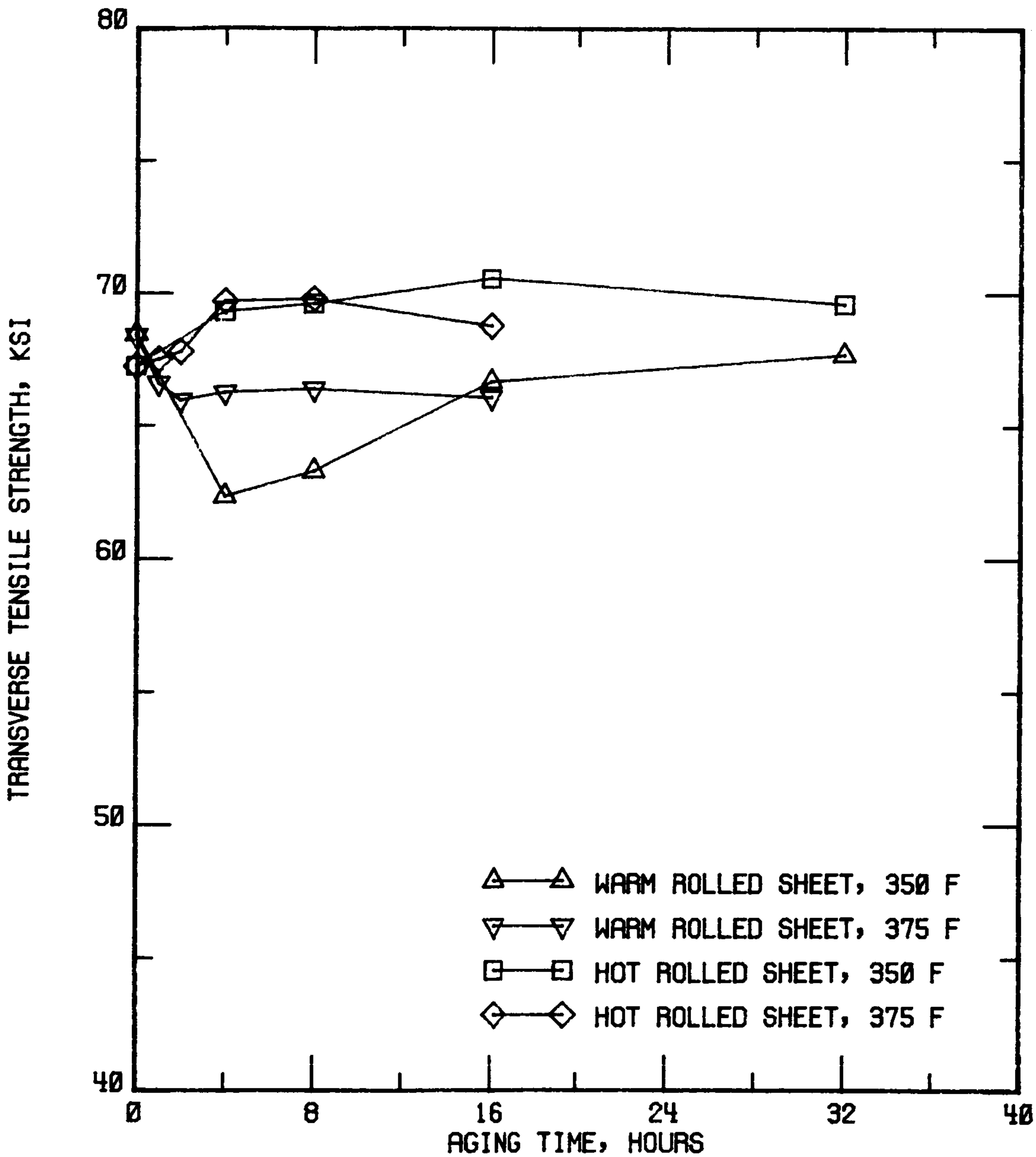


Figure 11. - Transverse tensile strength of two PM sheet variants as a function of aging at 350° and 375°F.

TABLE 9. - FRACTURE TOUGHNESS PROPERTIES OF 0.250 IN. THICK WARM ROLLED PLATE

Warm Rolled Plate (514163-1B)

Aging Condition	K_{ICH} (ksi-in. $^{1/2}$) Specimen 1	2	Avg.
"T3"			
L-T Orientation	75.05	79.99	77.52
T-L Orientation	75.28	60.97	68.13
Aged at 350 F			
L-T Orientation			
4 hours	74.33	85.89	80.11
8 hours	72.11		72.11
16 hours	62.36	63.10	62.73
32 hours	70.23		70.23
T-L Orientation			
4 hours	86.47	73.72	80.10
8 hours	63.13		63.13
16 hours	66.99	65.59	66.29
32 hours	63.29		63.29
Aged at 375 F			
L-T Orientation			
1 hour	69.91		69.91
2 hours	74.47	83.41	78.94
4 hours	83.20	84.01	83.61
8 hours	76.71		76.71
16 hours	55.96		55.96
T-L Orientation			
1 hour	72.40		72.40
2 hours	64.73	69.79	67.26
4 hours	63.28	59.25	61.27
8 hours	66.70		66.70
16 hours	66.91		66.90

conditions in sheet did not produce significant differences on the basis of the tear stength/yield strength ratio. When the L-T and T-L data are plotted together as in Figure 16, they describe a fairly consistent single behavior. The individual least squares fit to the data sets are also included on the plot.

TABLE 10. - FRACTURE TOUGHNESS PROPERTIES OF 0.250 IN. THICK HOT ROLLED PLATE

Hot Rolled Plate (514163-1A)

Aging Condition	K_{ICH} (ksi-in. $^{1/2}$) Specimen 1	2	Avg.
"T3"			
L-T Orientation	87.25	84.88	86.07
T-L Orientation	94.76	105.05	99.91
Aged at 350 F			
L-T Orientation			
4 hours	90.85	91.08	90.97
8 hours	87.72		87.72
16 hours	68.34	74.81	71.58
32 hours	74.82		74.82
T-L Orientation			
4 hours	93.79		93.79
8 hours	82.38		82.38
16 hours	82.60	82.46	82.53
32 hours	71.06		71.06
Aged at 375 F			
L-T Orientation			
1 hour	82.99		82.99
2 hours	79.99	81.99	80.99
4 hours	75.60	74.53	74.57
8 hours	65.28		65.28
16 hours	68.88		68.88
T-L Orientation			
1 hour	87.55		87.55
2 hours	103.04	100.02	101.53
4 hours	84.61	79.62	82.12
8 hours	85.47	80.17	82.82
16 hours	73.95		73.95

The unit propagation energy (UPE) of the PM sheet variants is plotted against yield strength in Figure 17. The lines represent the upper limit of the plotted data for each variant. The results exhibit the typical characteristics associated with UPE type analyses. It is noted that a similar behavior is observed in ingot metallurgy Al alloys. The PM sheet data showed a characteristic drop in toughness relative to strength at the underaged and overaged temper conditions. The L-T warm rolled toughness exhibited a distinct advantage in the underaged conditions, but the reverse was observed on overaging. In general, the hot rolled sheet variant led to marginally better combinations of UPE and yield strength, but also showed more scatter in UPE values. Additionally, the T-L hot rolled material strength and UPE combination was improved slightly over the T-L warm rolled condition combination.

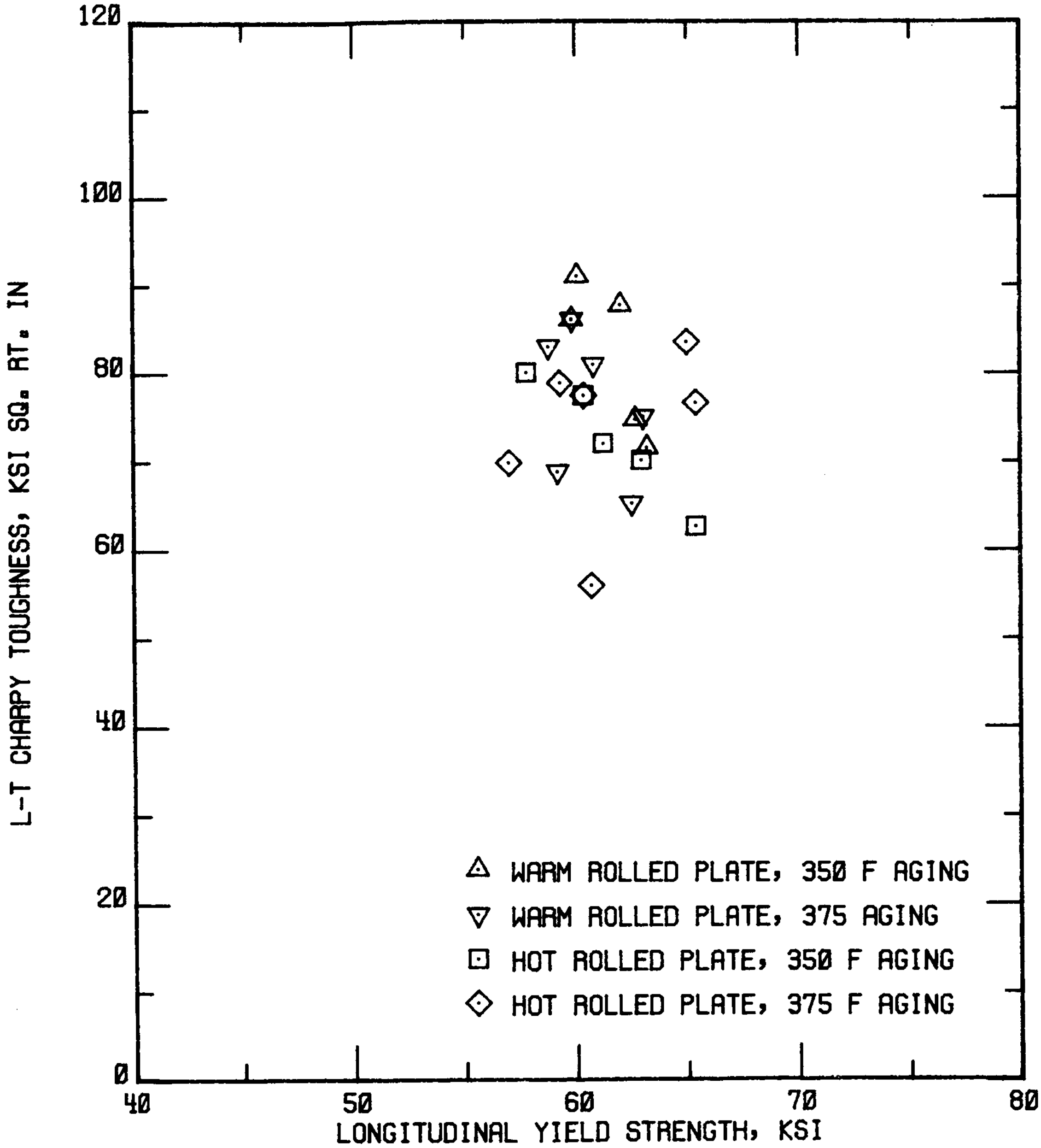


Figure 12. - Charpy fracture toughness vs. yield strength relationship for two PM plate variants in L-T orientation.

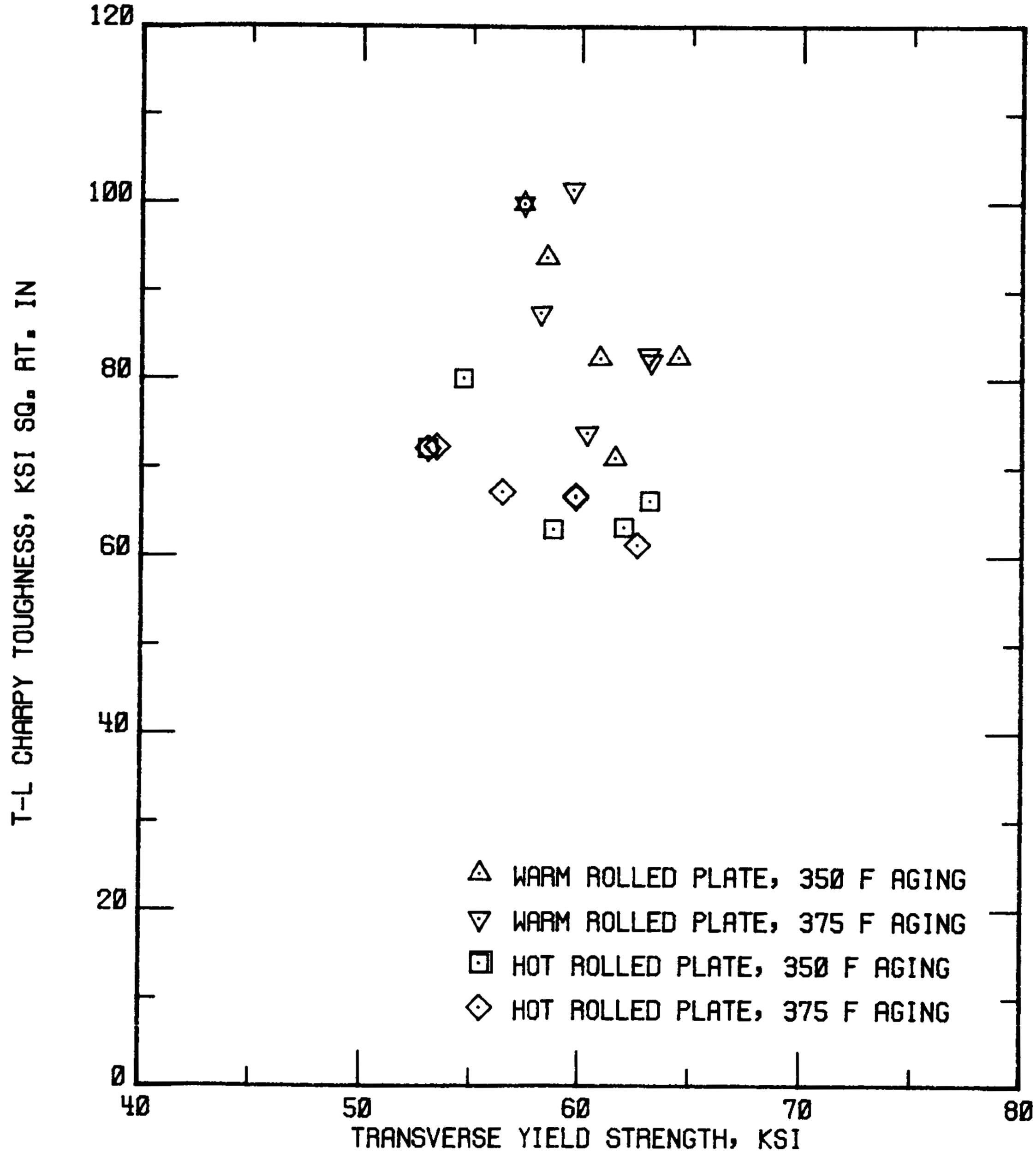


Figure 13. - Charpy fracture toughness vs. yield strength relationship for two PM plate variants in T-L orientation.

TABLE 11a. - FRACTURE TOUGHNESS PROPERTIES OF 0.070 IN. THICK WARM ROLLED SHEET

Warm Rolled Sheet (514163-CC), Aged at 350°F

Aging History	Orientation	Tear Strength (ksi)	Unit Propagation Energy in-lb/in (2)
0 hours*	L-T	(83.2)	(686)
		(84.0)	(901)
average		(83.6)	(795)
	T-L	(84.6)	(530)[1]
		(83.1)	(766)[1]
average		(83.9)	(650)[1]
4	L-T	(84.3)	(1055)
	T-L	(87.1)	(921)
8	L-T	(88.2)	(1053)
	T-L	(89.6)	(707)
16*	L-T	(85.2)	(519)
		(88.2)	(651)
average		(86.7)	(585)
	T-L	(88.4)	(429)
		(88.6)	(344)
average		(88.5)	(385)
32	L-T	(80.9)	(500)
	T-L	(90.6)	(414)

*Duplicate Tests
Note: 1 - Diagonal fracture, tear strength and UPE may be slightly high

TABLE 11b. - FRACTURE TOUGHNESS PROPERTIES OF 0.70 IN. THICK WARM ROLLED SHEET

Warm Rolled Sheet (514163-CC), Aged at 375°F

Aging History	Orientation	Tear Strength (ksi)	Unit Propagation Energy in-lb/in (2)
1 hour	L-T	(84.5)	(980)
	T-L	(88.8)	(695)
2*	L-T	(86.3)	(1171)
		(84.2)	(1011)
average		(85.3)	(1090)
	T-L	(87.2)	(703)
		(87.9)	(797)
average		(87.5)	(750)
4*	L-T	(90.9)	(735)
		(90.5)	(749)
average		(90.7)	(740)
	T-L	(87.9)	(464)
		(87.2)	(575)[1]
average		(87.5)	(646)
8	L-T	(68.0)	(429)[2]
	T-L	(86.0)	(240)[3]
16	L-T	(67.1)	(377)
	T-L	(84.7)	(595)

*Duplicate Tests
Notes: 1 - High initial loading (Energies invalid; not included in average)
2 - Diagonal fracture, tear strength and UPE may be slightly high
3 - Rapid fracture UPE is estimated but not valid

TABLE 12a. - FRACTURE TOUGHNESS PROPERTIES OF 0.070 IN. THICK HOT ROLLED SHEET

Hot Rolled Sheet (514163-CH), Aged at 350°F

Aging History	Orientation	Tear Strength (ksi)	Unit Propagation Energy in-lb/in (2)
0 hours*	L-T	(85.6)	(844)
		(81.4)	(891)
average		(83.5)	(865)
	T-L	(80.6)	(638)
		(83.9)	(556)
average		(82.2)	(595)
4	L-T	(86.3)	(1014)
	T-L	(86.3)	(645)
8	L-T	(87.9)	(850)
	T-L	(89.6)	(595)
16*	L-T	(90.5)	(668)
		(90.3)	(1098)
average		(90.4)	(885)
	T-L	(86.6)	(386)
		(86.8)	(432)
average		(86.8)	(405)
32	L-T	(89.6)	(564)
	T-L	(85.9)	(455)

*Duplicate Tests

TABLE 12b. - FRACTURE TOUGHNESS PROPERTIES OF 0.070 IN. THICK HOT ROLLED SHEET

Hot Rolled Sheet (514163-CH), Aged at 375°F

Aging History	Orientation	Tear Strength (ksi)	Unit Propagation Energy in-lb/in (2)
1 hour*	L-T	(85.7)	(915)
	T-L	(84.2)	(891)
2*	L-T	(87.6)	(811)
		(90.6)	(1054)[1]
average		(89.1)	(930)
	T-L	(87.4)	(716)
		(87.9)	(596)
average		(87.7)	(655)
4*	L-T	(87.7)	(740)
		(87.6)	(736)
average		(87.7)	(738)
	T-L	(87.4)	(402)
		(87.9)	(420)
average		(87.7)	(411)
8	L-T	(89.6)	(533)
	T-L	(91.3)	(521)
16	L-T	(89.6)	(533)
	T-L	(91.3)	(520)

*Duplicate Tests

Note: 1 - Crack path changed direction or was erratic, UPE may be high

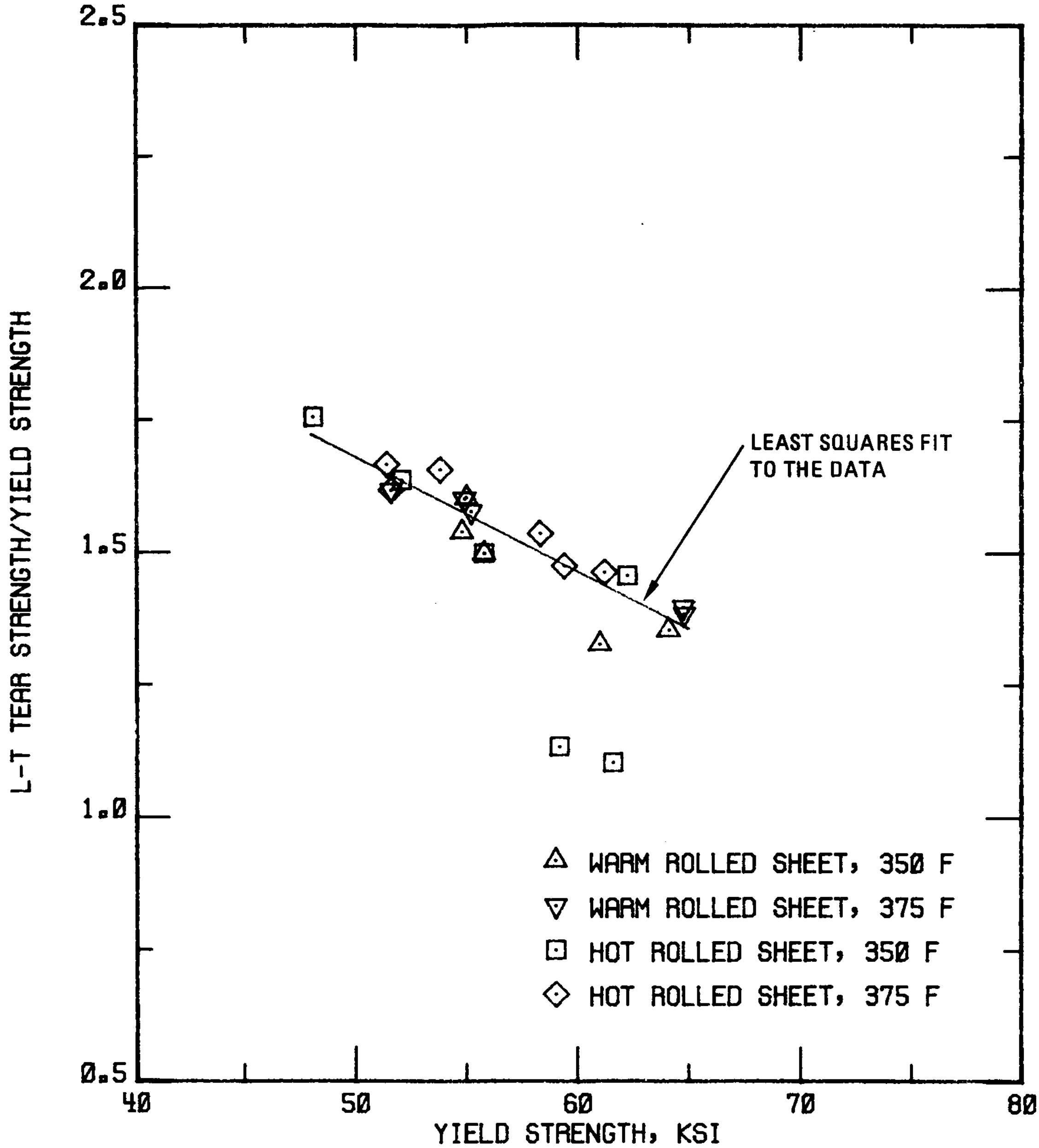


Figure 14. - Tear strength/yield strength ratio vs. yield strength data for two PM sheet variants in L-T orientation.

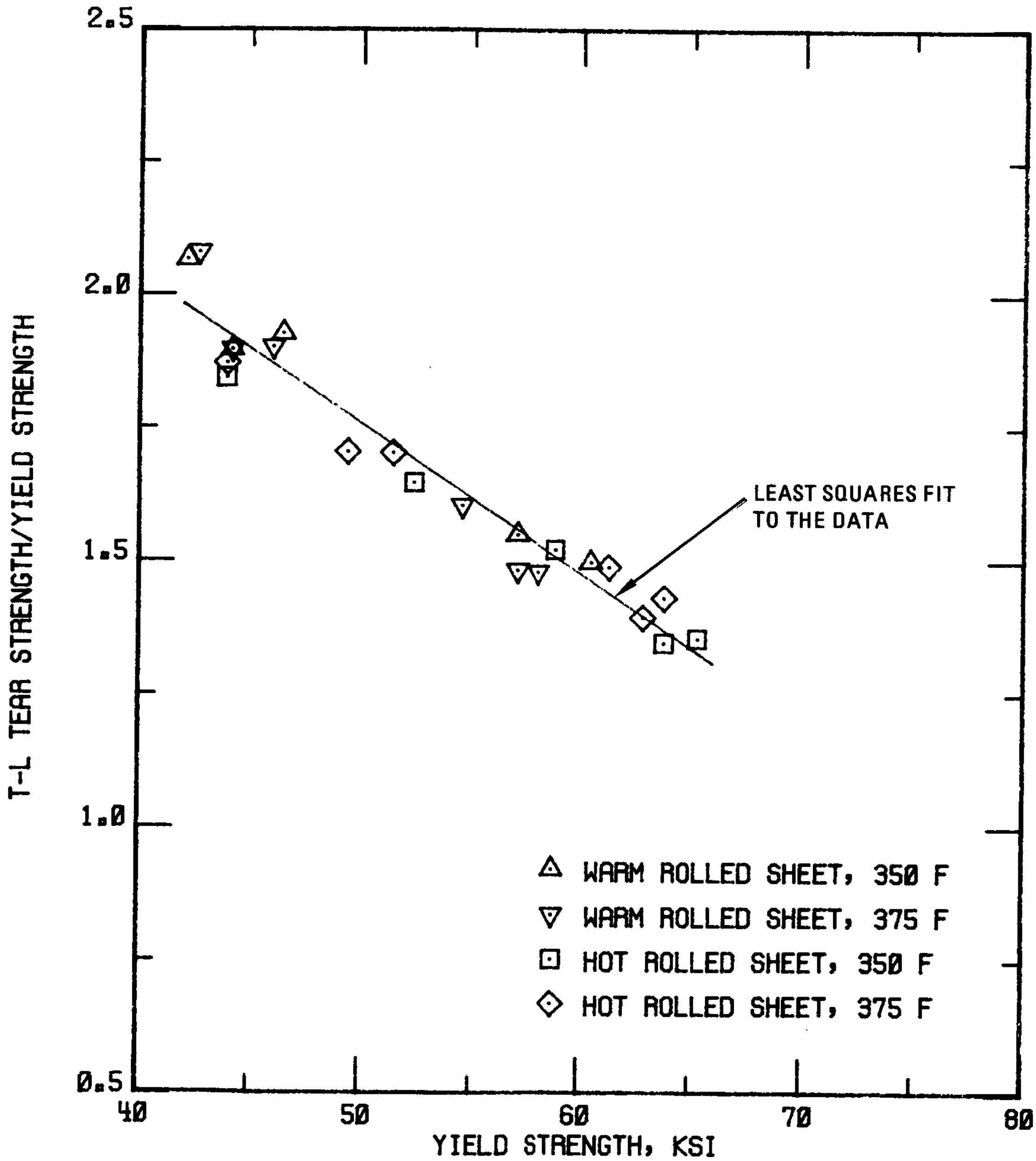


Figure 15. - Tear strength/yield strength ratio vs. yield strength data for two PM sheet variants in T-L orientation.

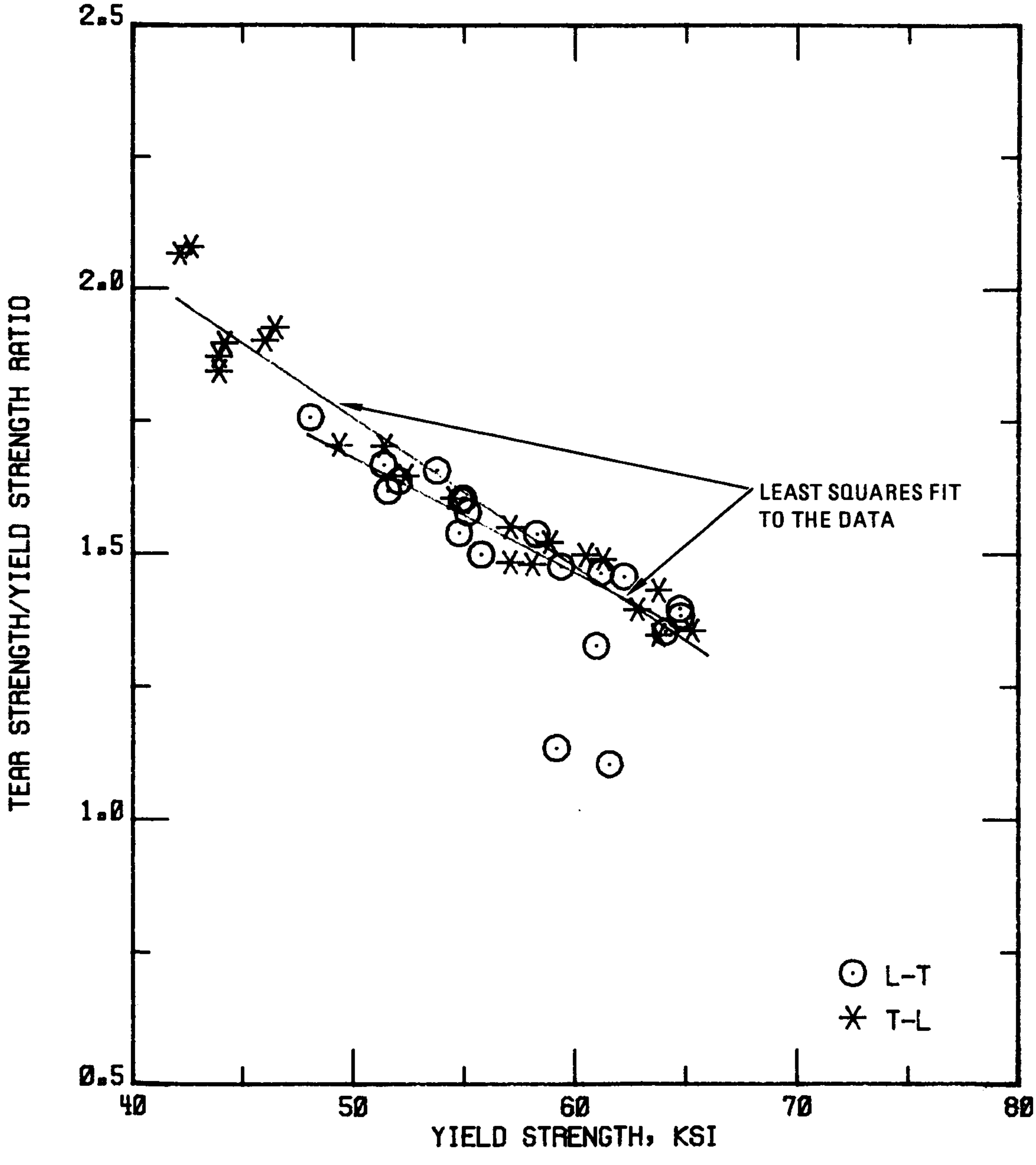


Figure 16. - Tear strength/yield strength ratio vs. yield strength results for PM sheet variants in both L-T and T-L orientations.

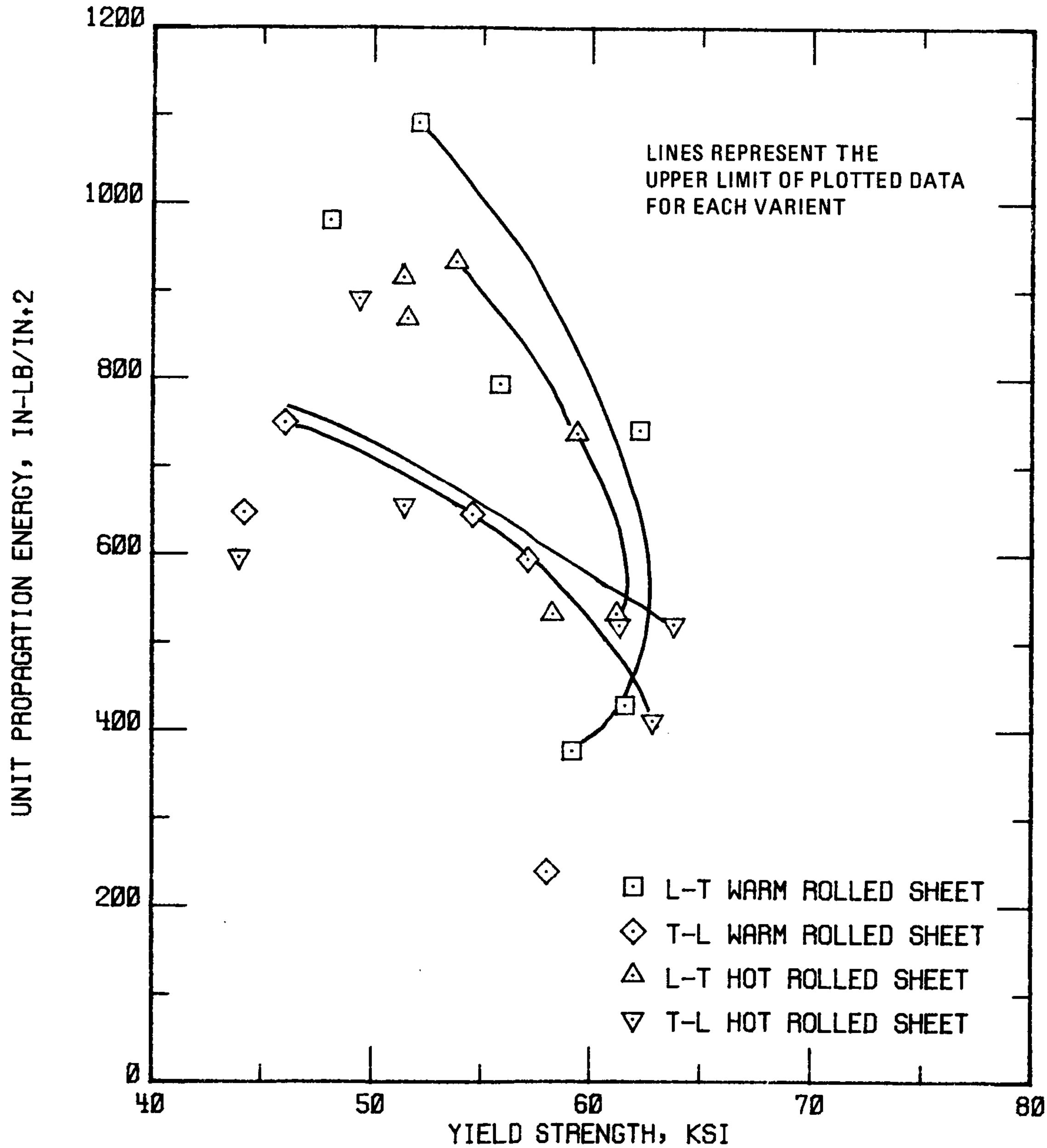


Figure 17. - Unit propagation energy vs. yield strength relationship for two PM sheet variants.

The fracture toughness indications for the entire set of PM sheet data show neither processing variant to possess a markedly different behavior. Toughness results in both gages and processing conditions do not appear to exhibit sufficiently large differences that clearly indicate that one processing variant is preferred. On the basis of these results, the hot rolled variant would be selected if strength - toughness is the major consideration. On the other hand, if maximum tensile strength is desired the warm rolled processing condition would be preferred. Additional testing is required to make a categorical decision as to the optimum processing variant. Supplemental factors influencing the final decision would involve both notched fatigue and corrosion performance.

3.4 Microstructural Characterization

The fine, predominantly dendritic, structure of the irregularly shaped powder particles is similar to observations made in the three previous investigations. The 1 to 3 micron secondary dendritic arm spacing indicates that cooling rates from 10^3 to 10^5 K/sec were operative during the atomization process. A finer dendritic structure was typically observed in the PM 2124 Al-Zr modified alloys as a consequence of Zr additions to the base alloy. Cellular powder structures indicative of a substantially higher undercooling were occasionally observed. Table 13 lists the phases identified by Guinier phase analysis in the as-atomized powders. The volume fraction of phases is ranked semiquantitatively by comparing the line intensity of a test film to that of an Al standard.

The presence of Al_2Cu detected in the two PM 2124 Al-Zr modified alloys (514042 and 514163) is a result of solute segregation which creates the cored, mostly dendritic, structure. During solidification, solute is rejected from the solid, thereby progressively increasing the liquid solute content. The changing compositional path of the freezing liquid is described by the classical liquidus diagram. For alloys with Cu/Mg ratios greater and less than 2.2:1.0; the freezing liquid follows the path to the left and right of the quasi-binary hump, respectively,

$$Al_{\text{solid solution}} + Al_2Cu + Al_2\,CuMg.$$

If the solidification rate is sufficiently high, the solute can be retained in metastable, supersaturated solid solution. At lower solidification rates Al_2CuMg, Al_2Cu, and Mg_2Si may precipitate during the cool-down to ambient temperatures after solidification of the last portion of liquid phase at the eutectic composition. Rapid age hardening occurs in PM Al alloys due to the promotion of rapid diffusion rates from the high concentration of quenched-in vacancies. Constituent phases that contain Mn, Fe, Ni, and Zr were not detected by Guinier analysis or metallographic examination of the as-polished powders at 1000X.

TABLE 13. - PHASE ANALYSIS IDENTIFICATION IN PM 2124 Al ALLOYS BY GUINIER X-RAY METHOD

Sample No.	Product	Phases Present								
		$CuAl_2$	Al_2CuMg	θ'	S'	$Al_{20}Cu_2Mn_3$	Al_9FeNi	Al_7Cu_2Fe	Tetragonal Al_3Zr	Cubic Al_3Zr
513707	Extrusion(1)	Trace	–	–	–	–	Med.	Med.	–	–
	Powder	–	V. Sml. -	–	–	–	Small +	–	–	–
513708	Extrusion(1)	Small	–	–	–	Med.	–	–	–	–
	Powder	Small	V. Sml. -	–	–	Poss. Sml.	–	–	–	–
513709	Extrusion(1)	Small	–	–	–	Small	–	–	–	–
	Powder	Small	–	–	–	Small	–	–	–	–
514041	Extrusion(2)	–	–	–	–	–	–	V. Sml.	–	–
	Powder	V. Sml.	–	–	V. Sml. +	–	–	–	–	–
514042	Extrusion(2)	–	–	–	–	–	–	–	Sml. +	Med.(3)
	Powder	V. Sml. +	–	–	V. Sml.	–	–	Trace	–	–
513305	Extrusion(2)	–	V. Sml. +	–	–	Med.	–	V. Sml. -	–	–
514163	Powder	V. Sml. +	–	–	V. Sml.	–	–	Trace	–	–

Notes: (1) Solution heat treated at 920°F, CWQ, stretched 1.5 – 2.0%, and naturally aged 4 days minimum.
(2) Solution heat treated at 935°F, CWQ, stretched 1.5 – 2.0%, and naturally aged 4 days minimum.
(3) Identified by TEM only. Quantity present is an estimated amount.

The microstructure of the candidate PM billets was examined by optical metallography at 500X and 1000X. Guinier analysis of the phases present in the billets indicated that intermetallic compounds were detected that are similar to those observed in homogenized IM 2024 Al billets. The advantage obtained by PM processing involves the fine size and distribution of billet grains and intermetallic particles that are normally present as large constituents in IM 2XXX Al alloys. The amount of primary soluble phases, Al_2Cu and Al_2CuMg, indicates that the segregation created during solidification is not completely eliminated by the precipitation and growth of intermetallic phases present in the atomized powder. The one hour holding time at 935°F during the vacuum preheat cycle may not be adequate to dissolve the large equilibrium Al_2Cu phases.

The intermetallic phases, grain structure, and crystallographic texture which comprises the microstructure of the PM 2124 Al-Zr modified materials are presented in the following sections. Metallographic results from the previous investigations are used where necessary to resolve the effect of compositional changes on property behavior in the current investigation. The phases identified in the naturally aged PM 2XXX Al and IM 2034 Al alloys are also listed in Table 13. The calculated volume fraction of coherent Al_3Zr and incoherent $Al_{20}Cu_2Mn_3$ which precipitates at the vacuum preheat and solution heat treatment temperatures for the PM 2124 Al-Mn modified and -Zr modified alloys are shown in Table 14. Undissolved Al_2Cu in the PM 2124 Al-Mn modified alloys is eliminated by decreasing the Cu content as undertaken in the -Zr modified alloy compositions. Despite the occurrence of undissolved Al_2Cu in PM 2124 Al, coarse constituents such as Al_2CuMg in the IM 2034 Al alloy are eliminated. The incoherent dispersoid, $Al_{20}Cu_2Mn_3$, was not identified in either of the PM 2124 Al-Zr modified alloys. The absence of other Mn containing intermetallic phases indicates that most of the Mn was retained in solid solution.

Tetragonal Al_3Zr and cubic Al_3Zr phases were detected only in the higher Zr content alloys, namely 514042 and 514163. The size and distribution of Al_3Zr can be controlled by the heating rate and preheat temperature. A decrease in the preheating rate from 90,000°F/hr. to less than 90°F/hr. has been reported to increase the recrystallization temperature of an IM Al-Zr-Mg alloy containing 0.17 wt. pct. Zr by nearly 360°F. The inhibition of recrystallization mechanisms was explained by the presence of a fine, coherent Al_3Zr phase distribution. Since the PM Al compacts undergo a slow heating rate of approximately 18 to 36°F/hr. between 800° and 935°F during the vacuum preheat cycle, a fine distribution of coherent Al_3Zr is expected. The copious precipitation of cubic Al_3Zr throughout the matrix of the PM 2124 Al-Zr modified alloy extrusion was demonstrated in a prior contract effort. Relative to $Al_{20}Cu_2Mn_3$ in the PM 2124 Al-Mn modified alloys, and Al_9FeNi and Al_7Cu_2Fe in other PM 2XXX Al alloy systems, the Al_3Zr phase is much finer and uniformly distributed. Tetragonal Al_3Zr also occurs as coarser, more widely spaced rectangular shaped particles, typically less than 1.0 μm in length.

The alloy microstructure of the slab, plate, and billet was examined by optical metallographic and crystallographic texture techniques. Figure 18 shows orthogonal views of the slab at the T/4 and T/2 positions. It is obvious that the starting slab microstructure is inhomogeneous, with a decidedly coarser, uniaxed grain morphology at the T/4 position, while at the T/2 location a pancake grain structure is present. The surface view of both sections suggests that some recrystallization or grain growth may have occurred in both positions, but the grain size is qualitatively in the range of the initial powder size distribution. The micrographs also illustrate that the slab forging quite expectedly possessed an inhomogeneous strain distribution through the thickness. The $\{111\}$ x-ray pole figures shown in Figures 19 and 20 reflected this metallographic observation, indicating the presence of a stronger deformation texture in the T/2 position than the T/4 position (maximum intensity of 9.8R (times random) in the former and 2.69R (times random) in the latter).

TABLE 14. - CALCULATION OF HYPOTHETICAL VOLUME FRACTION OF DISPERSOIDS IN SEVERAL PM 2XXX Al ALLOY COMPOSITIONS

Sample No.	Element (Wt. Pct.)	Dispersoid (1) Type	Estimated Volume Fraction (Pct.)
513707	1.53 Fe, 1.73 Ni	Al_9FeNi, Al_7Cu_2Fe	10.51 (2)
513708	1.50 Mn	$Al_{20}Cu_2Mn_3$	4.99 (3)
513709	0.51 Mn	$Al_{20}Cu_2Mn_3$	1.15 (3)
513887	0.18 Mn	$Al_{20}Cu_2Mn_3$	0.0 (3)
513888	1.03 Fe, 0.93 Ni	Al_9FeNi, Al_7Cu_2Fe	6.71 (2)
513889	–	–	–
514041	0.12 Zr	Al_3Zr	0.09 (4)
514042	0.60 Zr	Al_3Zr	0.69 (4)
514163	0.60 Zr	Al_3Zr	0.69 (4)

Notes: (1) Ignores Mg_2Si phase which is assumed to be present in the same amount in all PM Al Alloys.
(2) Assumes no solid solubility and that all excess Cu over 2.5 wt. pct. is used to form Al_7Cu_2Fe.
(3) Solubility is approximately 0.20 wt. pct. at 920°F.
(4) Solubility is approximately 0.07 wt. pct. at 935°F.

The plate microstructure at the T/2 thickness position is displayed in Figure 21 for the two processing variants after solution heat treatment. The micrographs suggest that recrystallization and/or grain growth occurred in both PM processing variants. Substantially more recrystallization was observed to occur in the hot rolled variant. As could be expected there was a gradient of increasing grain size toward the surface of both rolled products. This was more evident in the warm rolled variant which had a smaller grain size at the centerline location. At near-surface positions the difference in grain structures between the two variants was not significantly large.

The $\{111\}$ x-ray pole figures for these two plate variants are given in Figures 22 and 23 in the heat treated condition at the T/2 plane. Both indicate the presence of a mixed texture consisting of the typical deformation texture, $\{112\} \langle 1\bar{1}0 \rangle + \{123\} \langle 63\bar{4} \rangle$, and possibly a component of the usual cube $\{100\} \langle 001 \rangle$ recrystallized texture. The recrystallized cube texture was determined to be stronger and the deformation component was weaker in the hot rolled variant, supporting the observation of a relatively large recrystallized grain size in this variant.

The grain structure of the two PM variants of sheet are shown in Figure 24. In this figure the T/2 section corresponds to the lower edge of the orthogonal sections, while the T/4 and near-surface sections correspond to the upper edge of the optical micrographs. The warm rolling schedule produced a more inhomogeneous microstructure consisting of very fine recrystallized

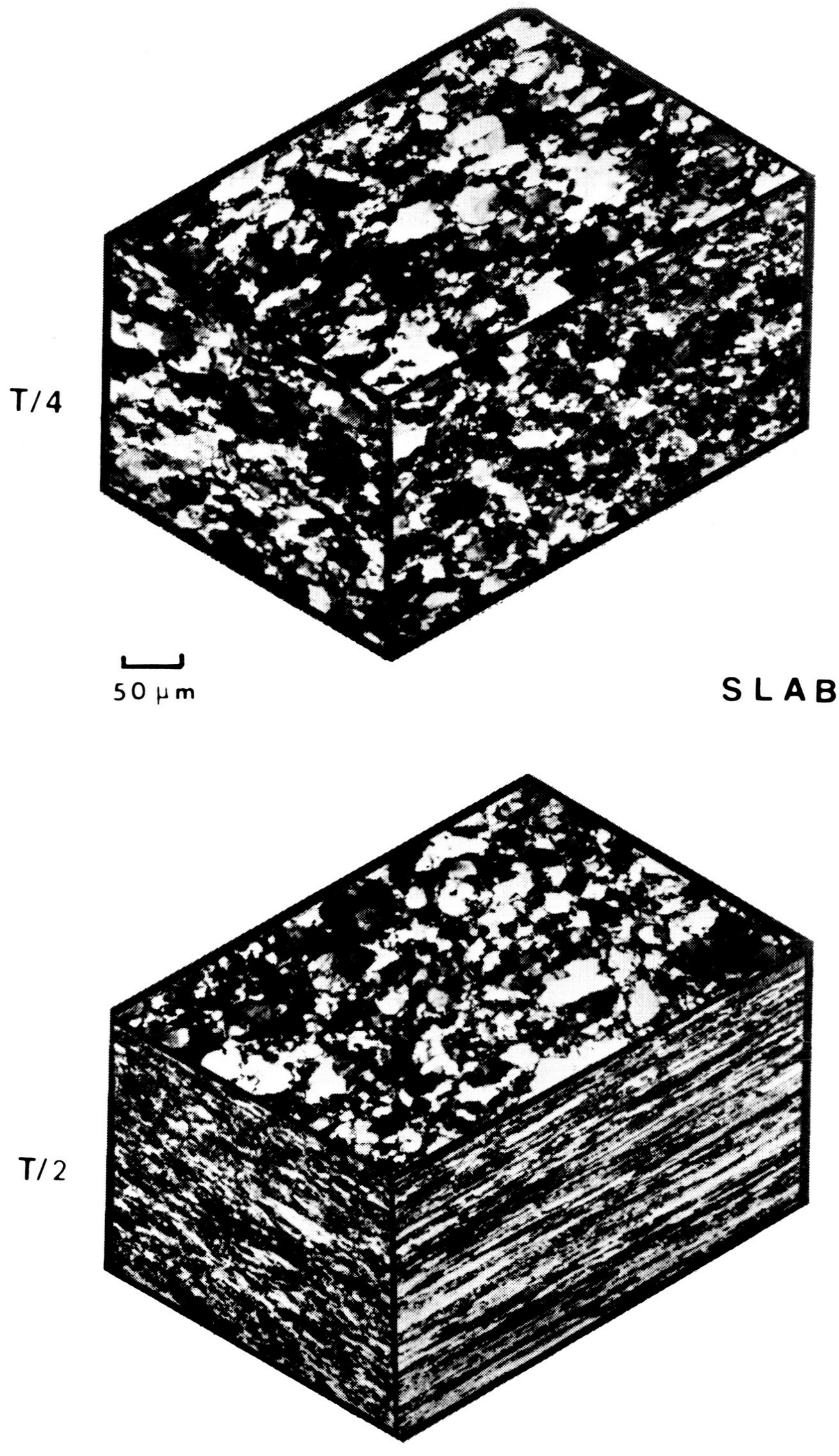


Figure 18. - Optical microstructures of PM forged slab at T/4 and T/2 positions.

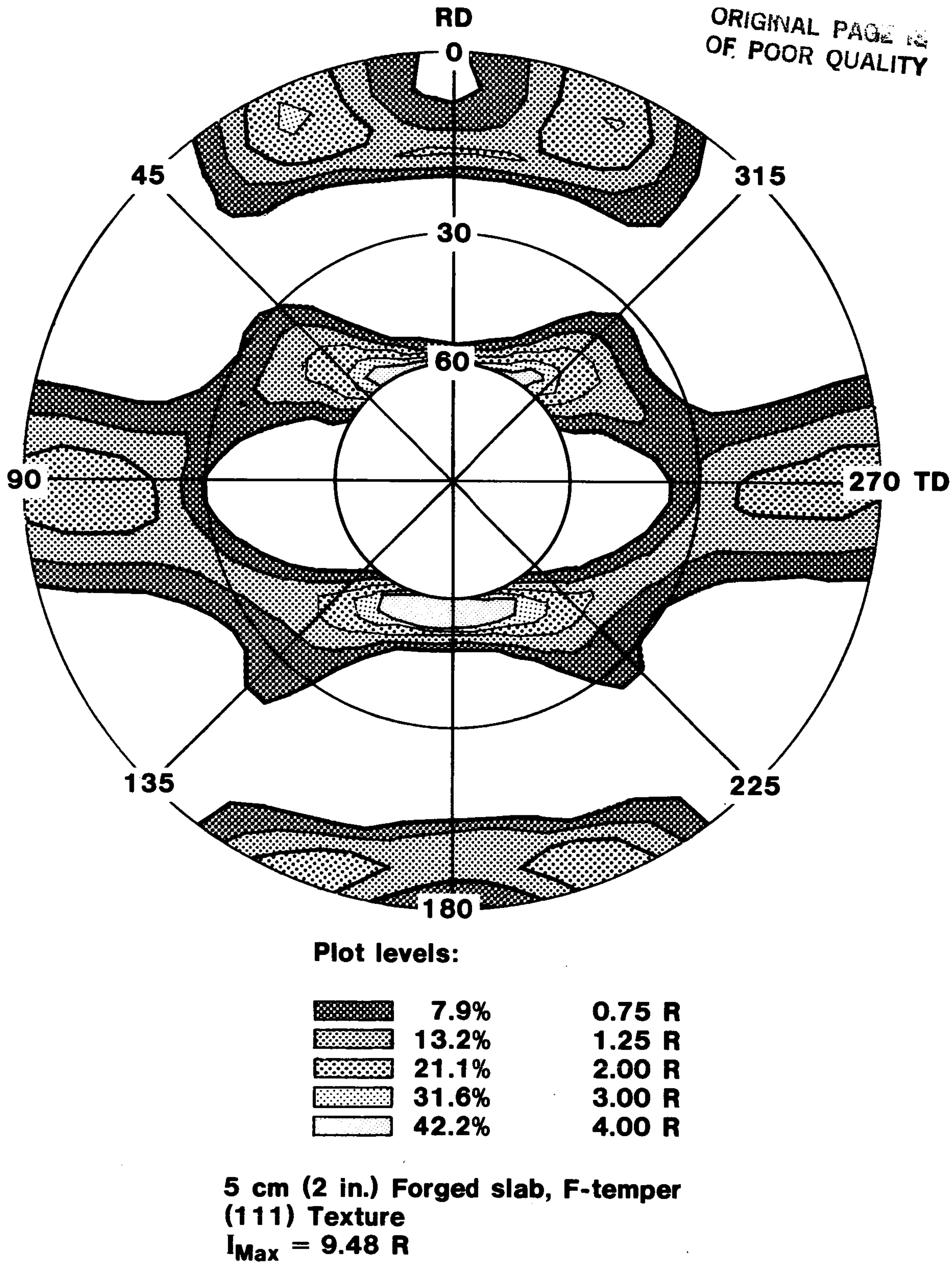
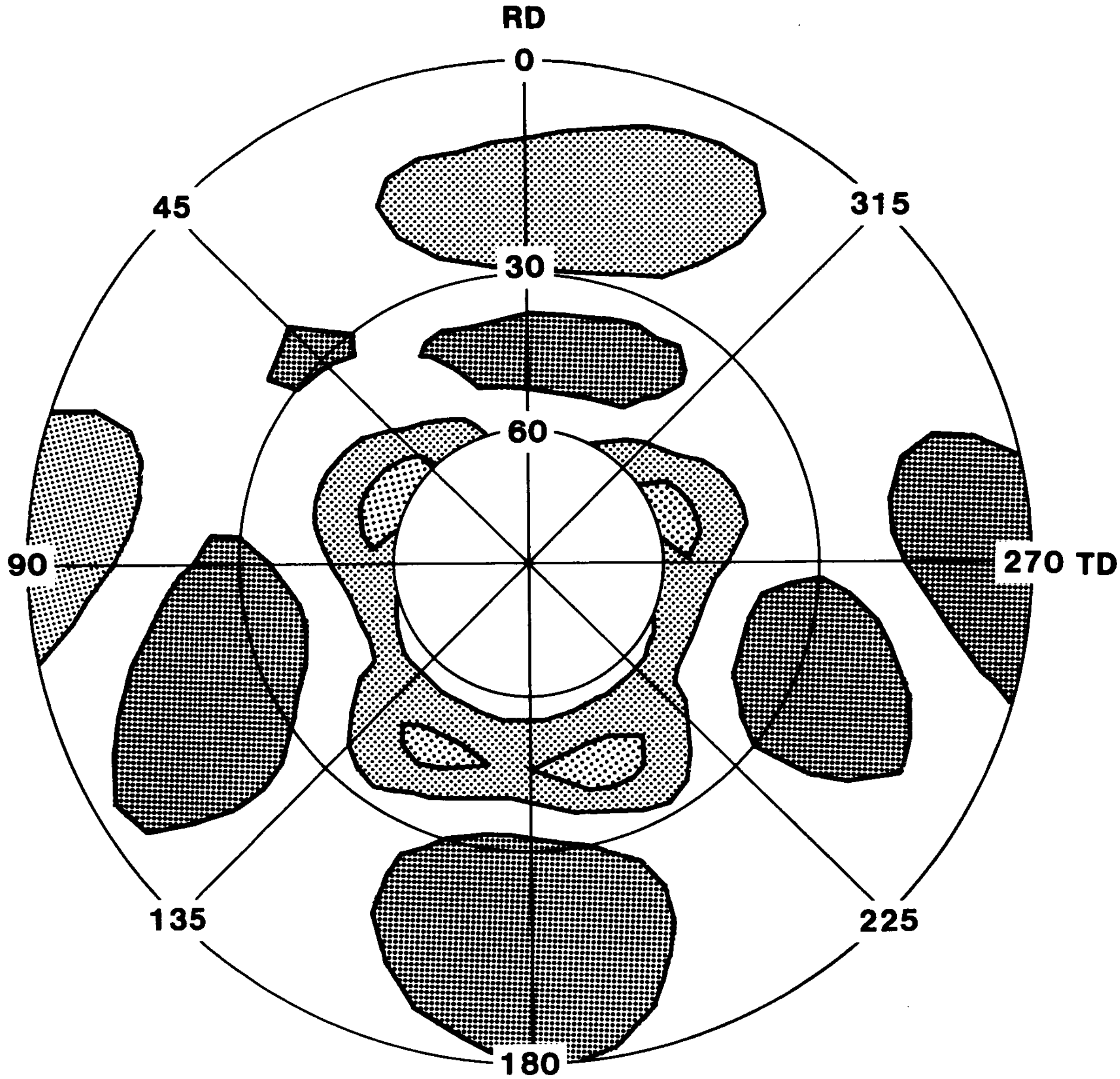


Figure 19. - {111} x-ray pole figure of PM forged slab at T/2 position.



Plot levels:

27.9%	0.75 R
46.4%	1.25 R
74.3%	2.00 R
111.5%	3.00 R
148.6%	4.00 R

5 cm (2 in.) Forged slab, F-temper
(111) Texture
I_{Max} = 2.69 R

Figure 20. - {111} x-ray pole figure of PM forged slab at T/4 position.

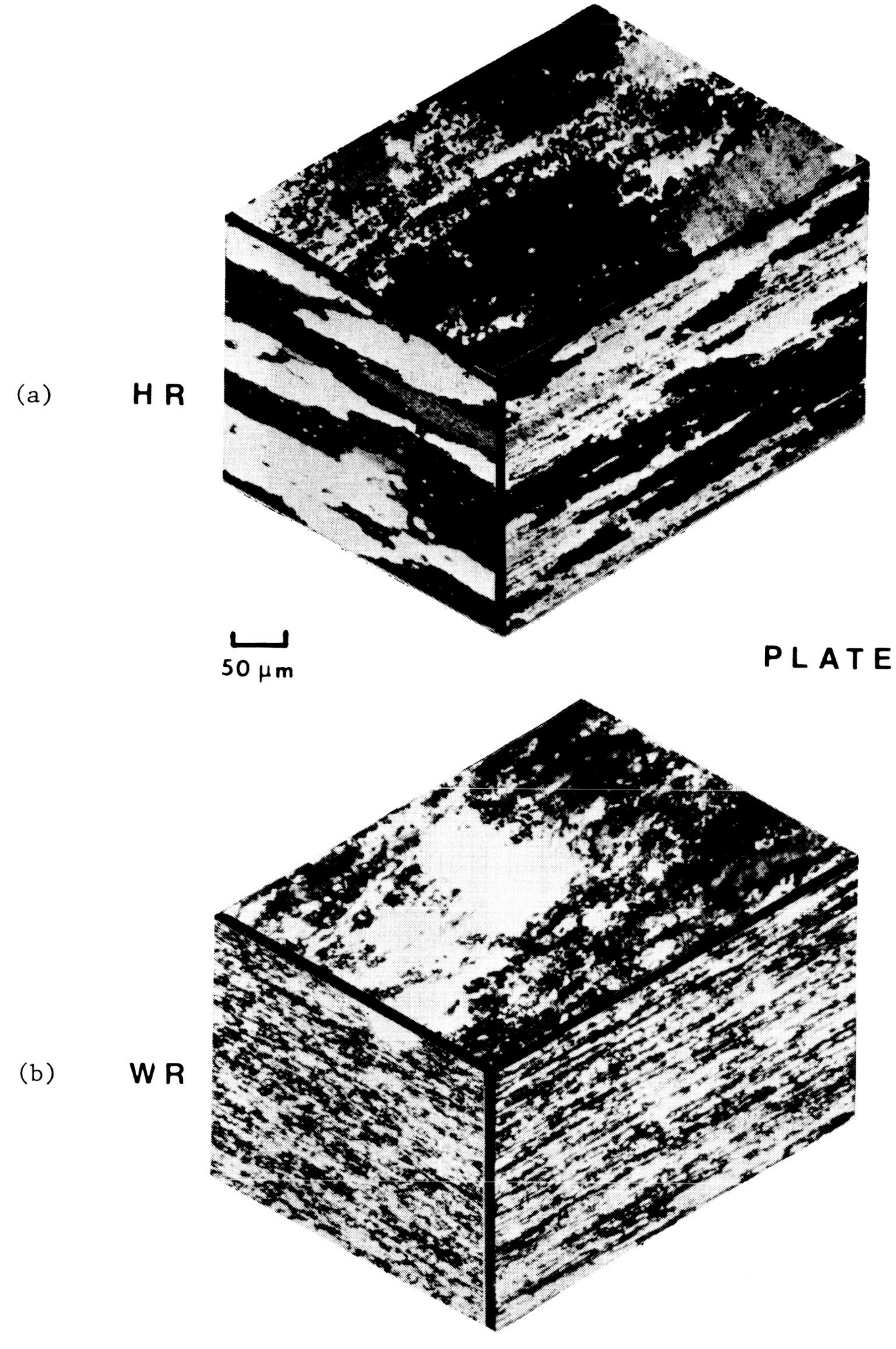


Figure 21. - Optical microstructures of PM plate variants at T/2 position: (a) hot rolled condition and (b) warm rolled condition.

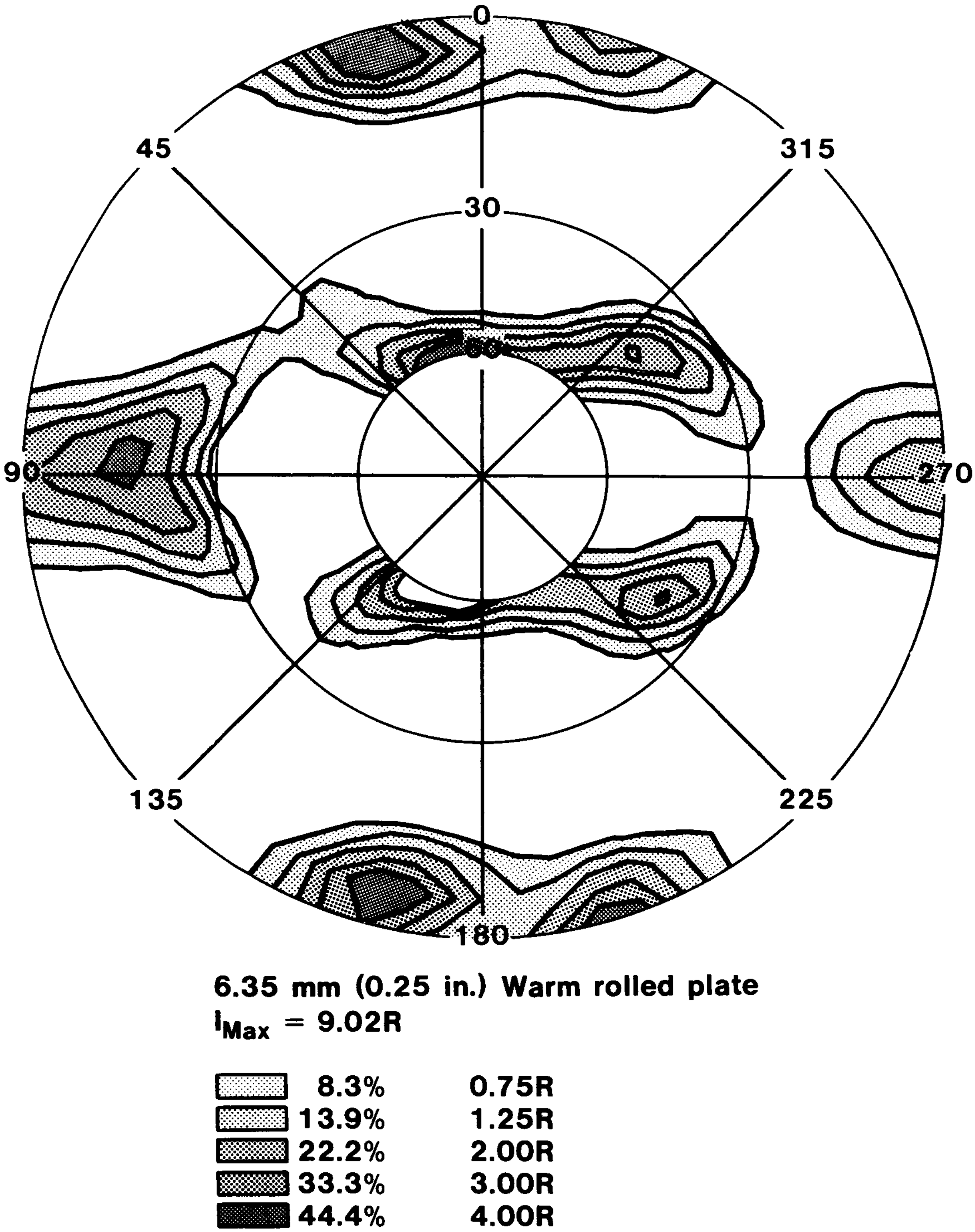


Figure 22. - {111} x-ray pole figure of PM warm rolled plate variant at T/2 position, solution heat treated temper.

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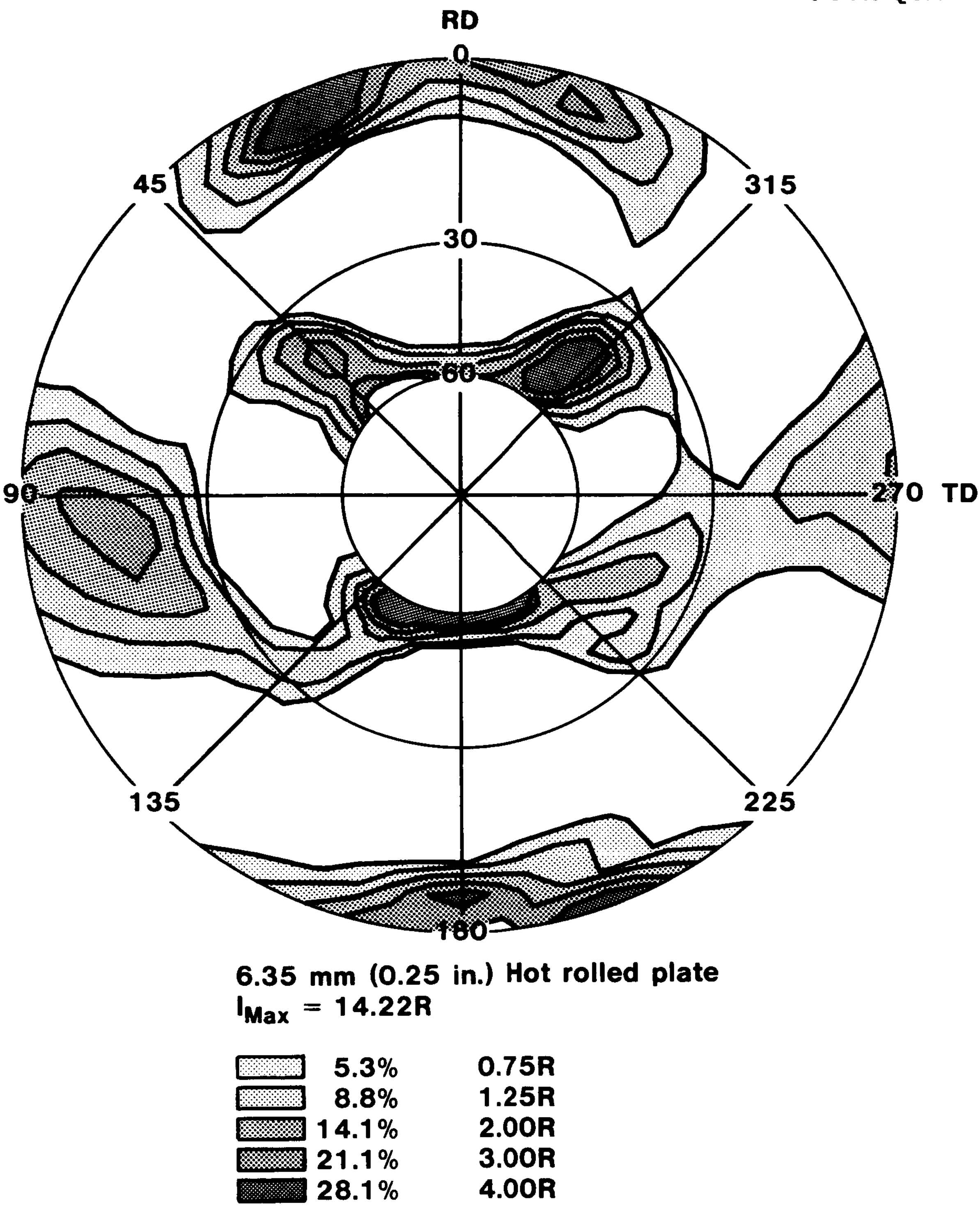


Figure 23. - {111} x-ray pole figure of PM hot rolled plate variant at T/2 position, solution heat treated temper.

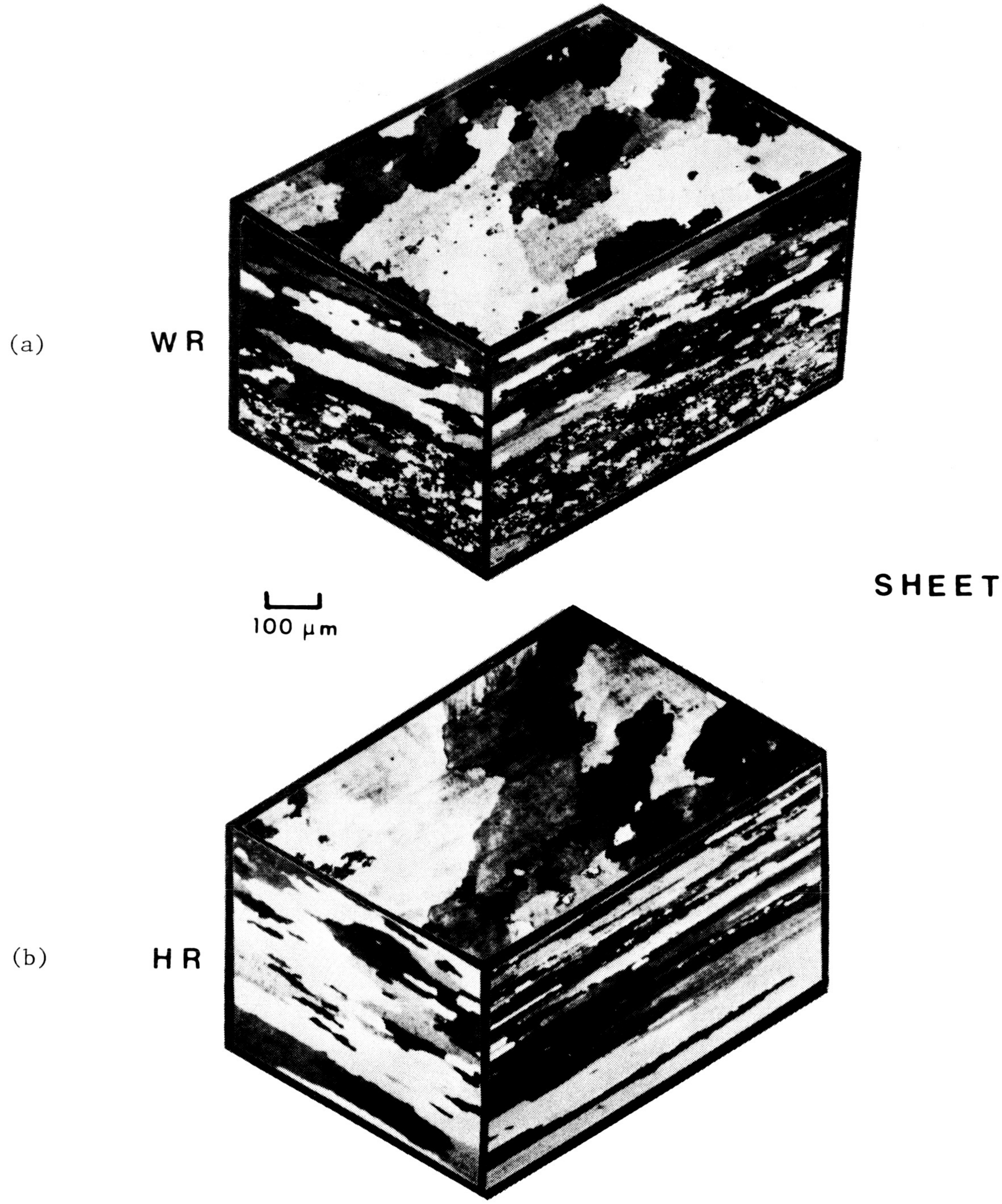


Figure 24. - Optical microstructures of PM sheet variants at T/2 and T/4 positions: (a) warm rolled condition and (b) hot rolled condition.

grains at the centerline position, with a much larger pancake recrystallized grain structure near the sheet surfaces. There also was a slight variation in grain structure for the hot rolled sheet, but this variant generally was totally recrystallized to a large pancake grain structure.

The $\{111\}$ and $\{200\}$ pole figures for the two PM sheet variants are shown in Figures 25 to 32 for both the -F temper and the solution heat treated conditions in order to establish the recrystallization processes as a function of solutionizing treatment. Figures 25 and 26 represent the -F temper sheet textures. These figures indicate that the -F temper sheet had a typically well defined sheet texture development as observed in the PM plate materials (Figures 22 and 23). Figures 27 and 28 show the same x-ray pole figures for the hot rolled variant. The hot rolled texture is much less well defined, with a maximum intensity in the pole figure decreased by about 25 percent. There is also a component of recrystallization in the pole figure indications that is present in the solution treated warm rolled variant, but not in the -F temper warm rolled variant. The predominate texture in the warm rolled -F temper is the standard Al alloy rolling texture, while apparently either dynamic recovery/recrystallization or post deformation static recrystallization occurred in the hot rolled processing condition. This led to a reduction in the sharpness of the deformation texture and contributed to a component of the recrystallization texture. Figures 29 and 30 show the two x-ray pole figures of the solution treated warm rolled variant. The PM alloy sheet has completely recrystallized, with the -F temper rolling texture being replaced by a more complex recrystallized texture. These recrystallized components match with several $\{110\}\langle uvw\rangle$ and $\{hkl\}\langle 001\rangle$ textures, particularly the $\{110\}\langle 001\rangle$, $\{110\}\langle 3\bar{3}2\rangle$, and $\{320\}\langle 001\rangle$, as well as a possible $\{111\}\langle 1\bar{1}0\rangle$ component.

A comparison of Figures 20 and 30 with Figures 31 and 32, indicate that not only did a different -F temper texture evolution occur in hot rolling, but also a different recrystallization texture developed on solution treatment of the hot rolled processing variant. The $\{200\}$ x-ray pole figure in Figure 31 shows a very weak contribution of the $\{100\}\langle 001\rangle$ cube texture and two additional complex textures. An orientation distribution function (ODF) analysis suggests that the two recrystallized components are best represented by the ideal $\{103\}\langle 31\bar{1}\rangle$ and $\{104\}\langle 47\bar{1}\rangle$ textures. The relative strengths of these textures for the two processing variants were about the same as observed in the -F temper textures.

A note of caution is advised in placing too much emphasis on the specific textures identified in the solution treated hot rolled variant due to the relatively coarse grain sizes. This situation is known to contribute to a less satisfactory sampling of the total distribution of grain orientations. It appears that the important significance of these texture analyses indicate that the PM alloys exhibited typical deformation sheet textures in the -F temper to 0.070 in. thick gages, with the warm rolled variant showing the stronger deformation texture development. The sheet gages of both processing

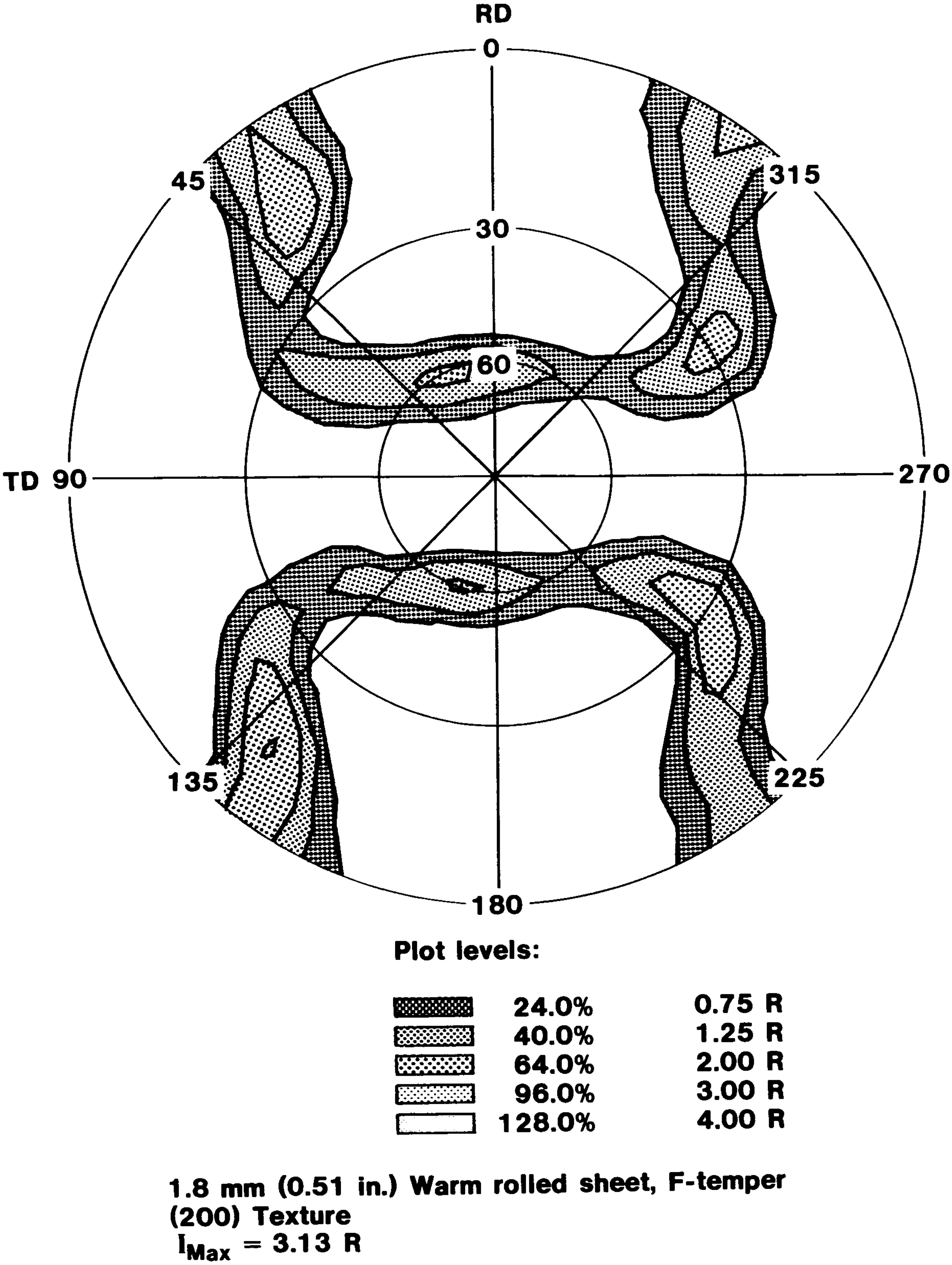
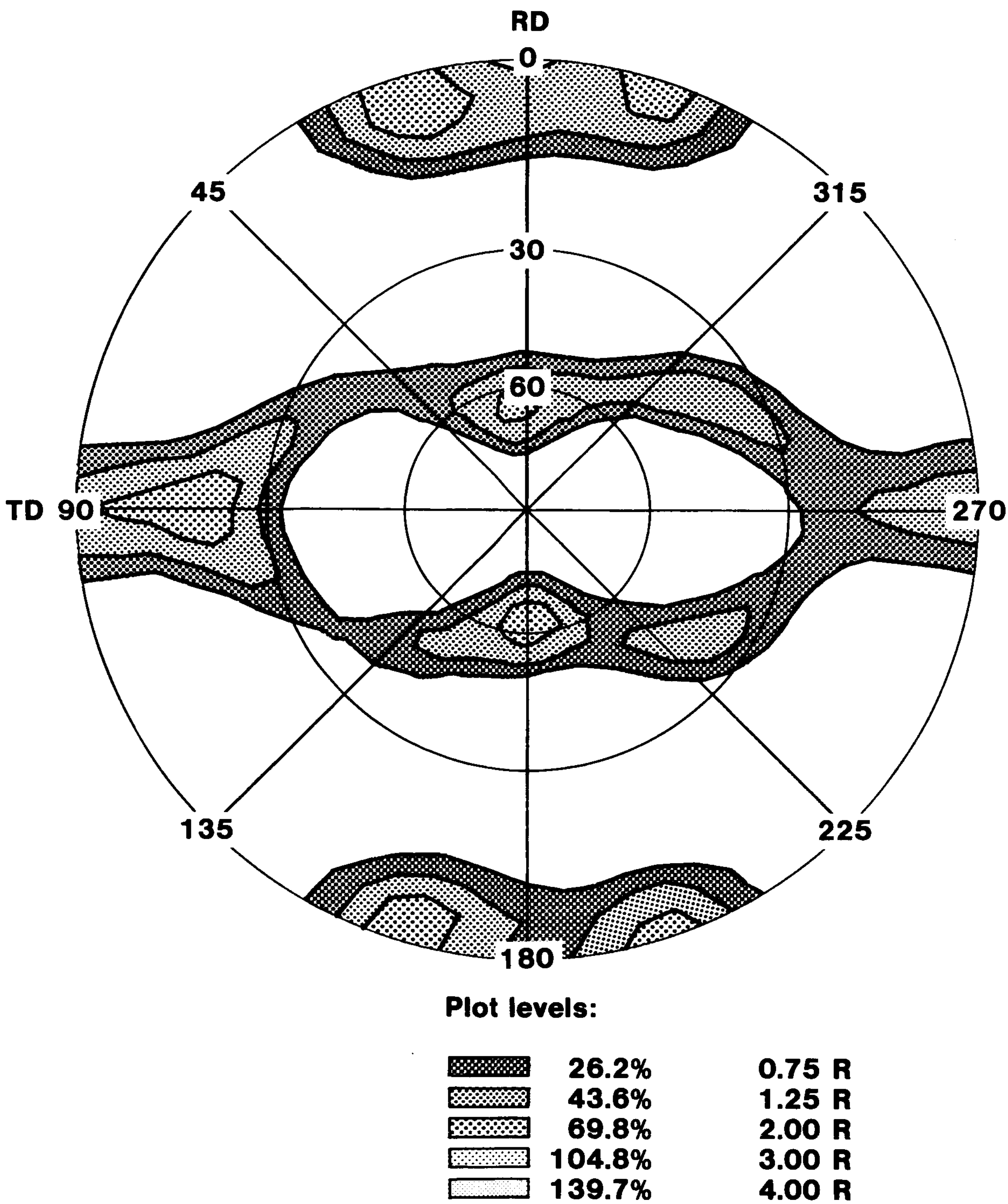
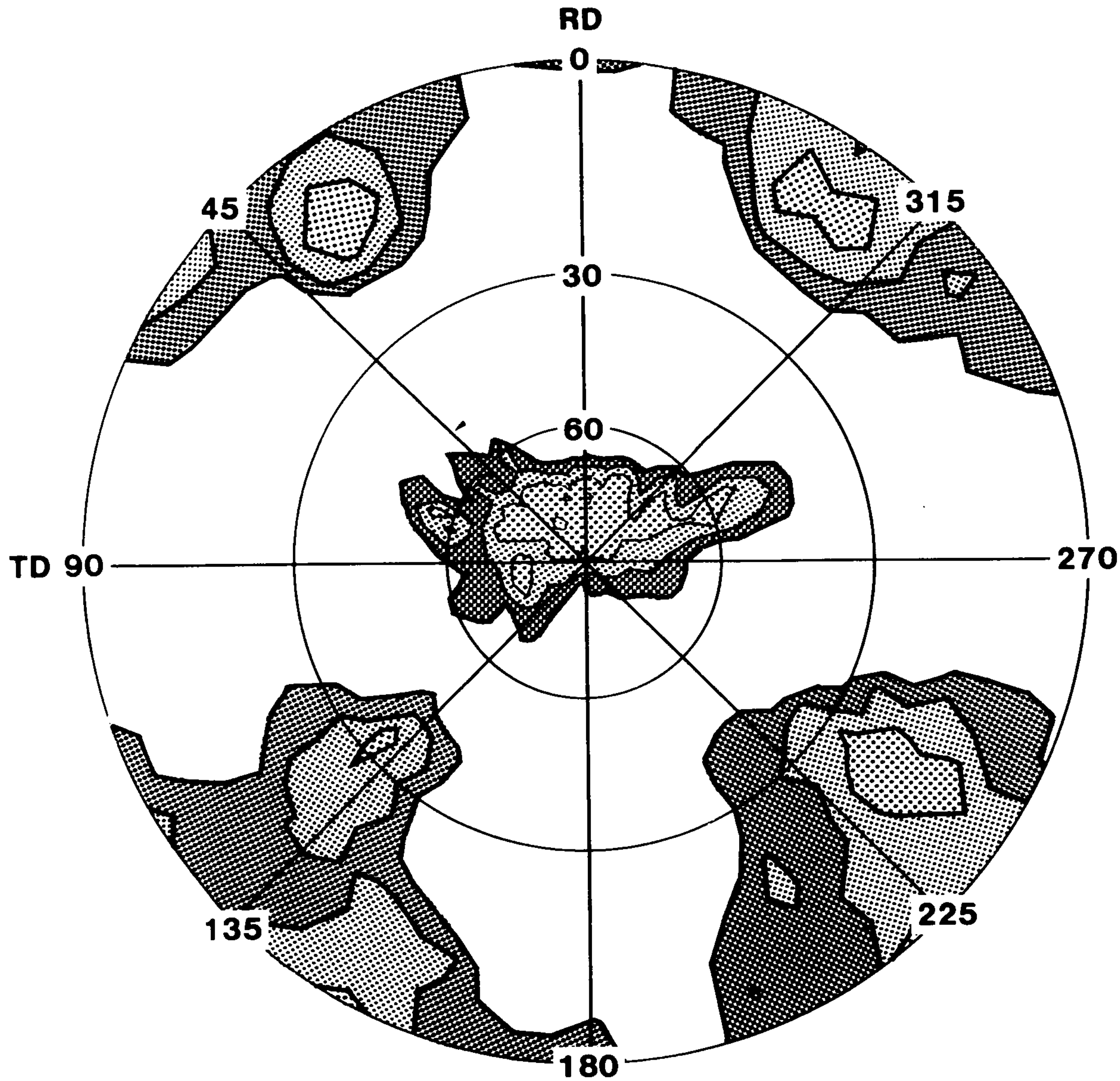


Figure 25. - {200} x-ray pole figure of PM warm rolled sheet variant at T/2 position, -F or as-fabricated temper.



1.8 mm (0.51 in.) Warm rolled sheet, F-temper
(111) Texture
I_{Max} = 2.86 R

Figure 26. - {111} x-ray pole figure of PM warm rolled sheet variant at T/2 position, -F or as-fabricated temper.



Plot levels:

▩	23.3%	0.75 R
▩	38.8%	1.25 R
▩	62.1%	2.00 R
▩	93.1%	3.00 R
☐	124.1%	4.00 R

1.8 mm (0.07 in.) Hot rolled sheet, F-temper
(200) Texture
I_{Max} = 3.22 R

Figure 27. - {200} x-ray pole figure of PM hot rolled sheet variant at T/2 position, -F or as-fabricated temper.

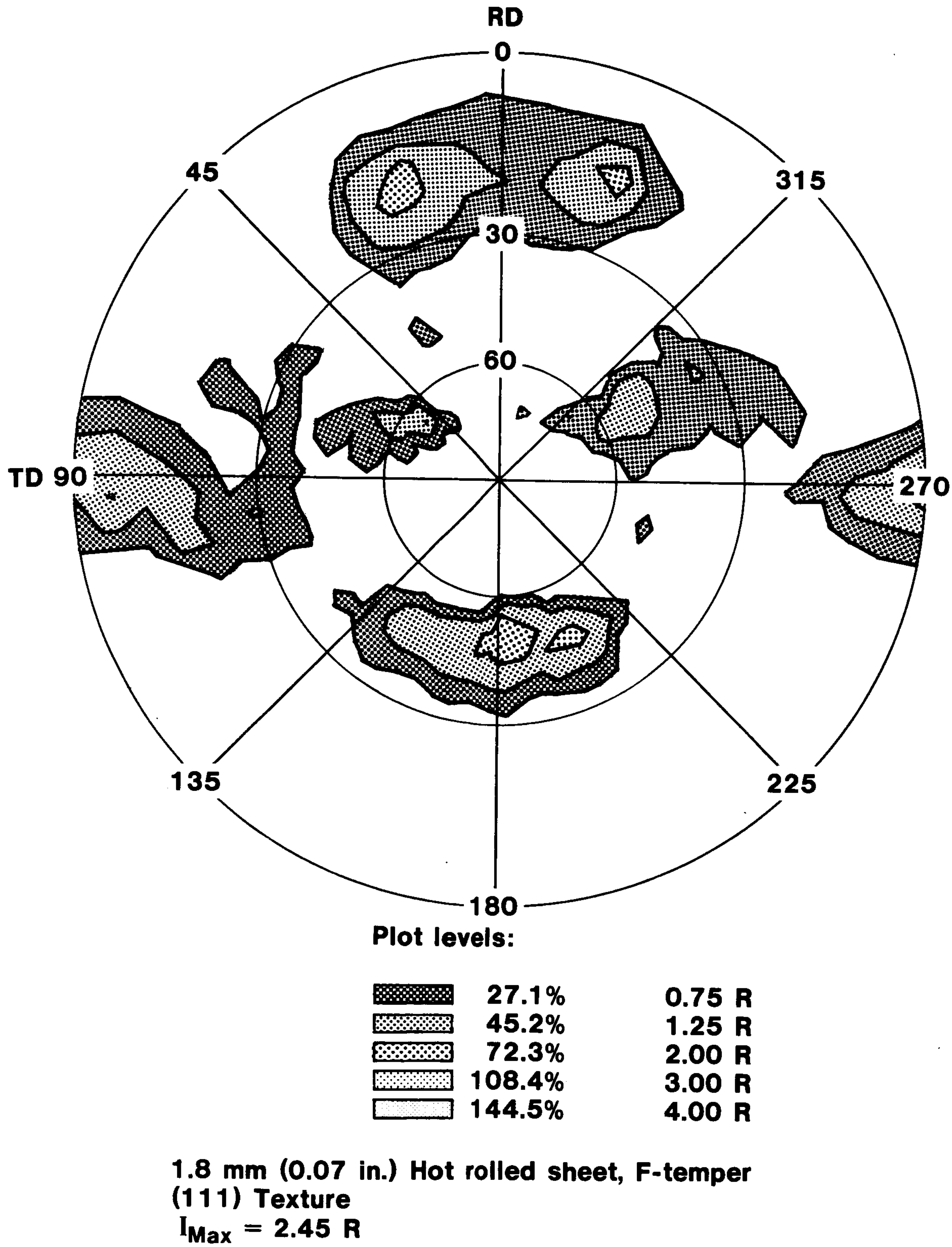


Figure 28. - {111} x-ray pole figure of PM hot rolled sheet variant at T/2 position, -F or as-fabricated temper.

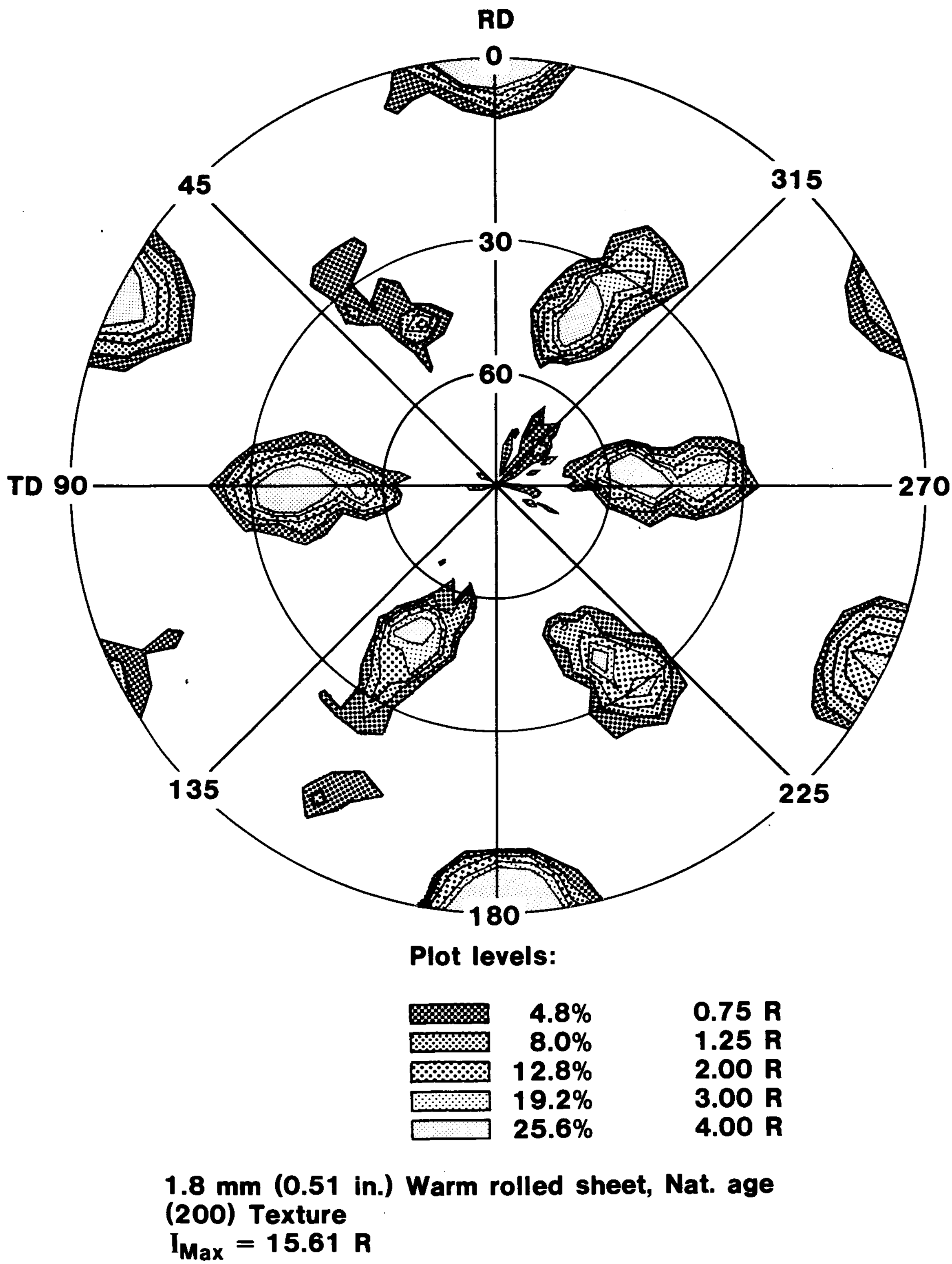
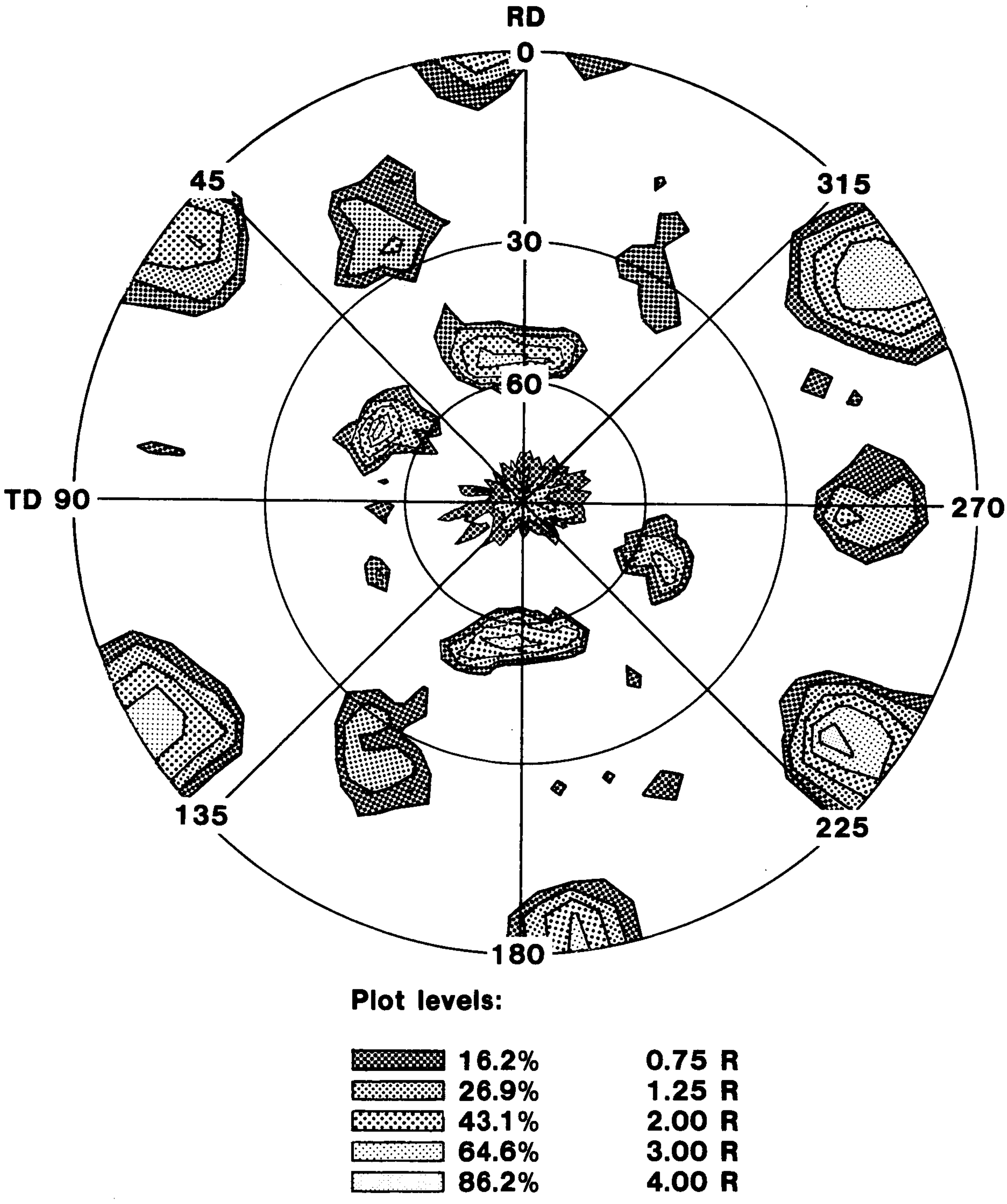


Figure 29. - {200} x-ray pole figure of PM warm rolled sheet variant at T/2 position, solution heat treated temper.



1.8 mm (0.07 in.) Warm rolled sheet, Nat. age
(111) Texture
I_{Max} = 9.21 R

Figure 30. - {111} x-ray pole figure of PM warm rolled sheet variant at T/2 position, solution heat treated temper.

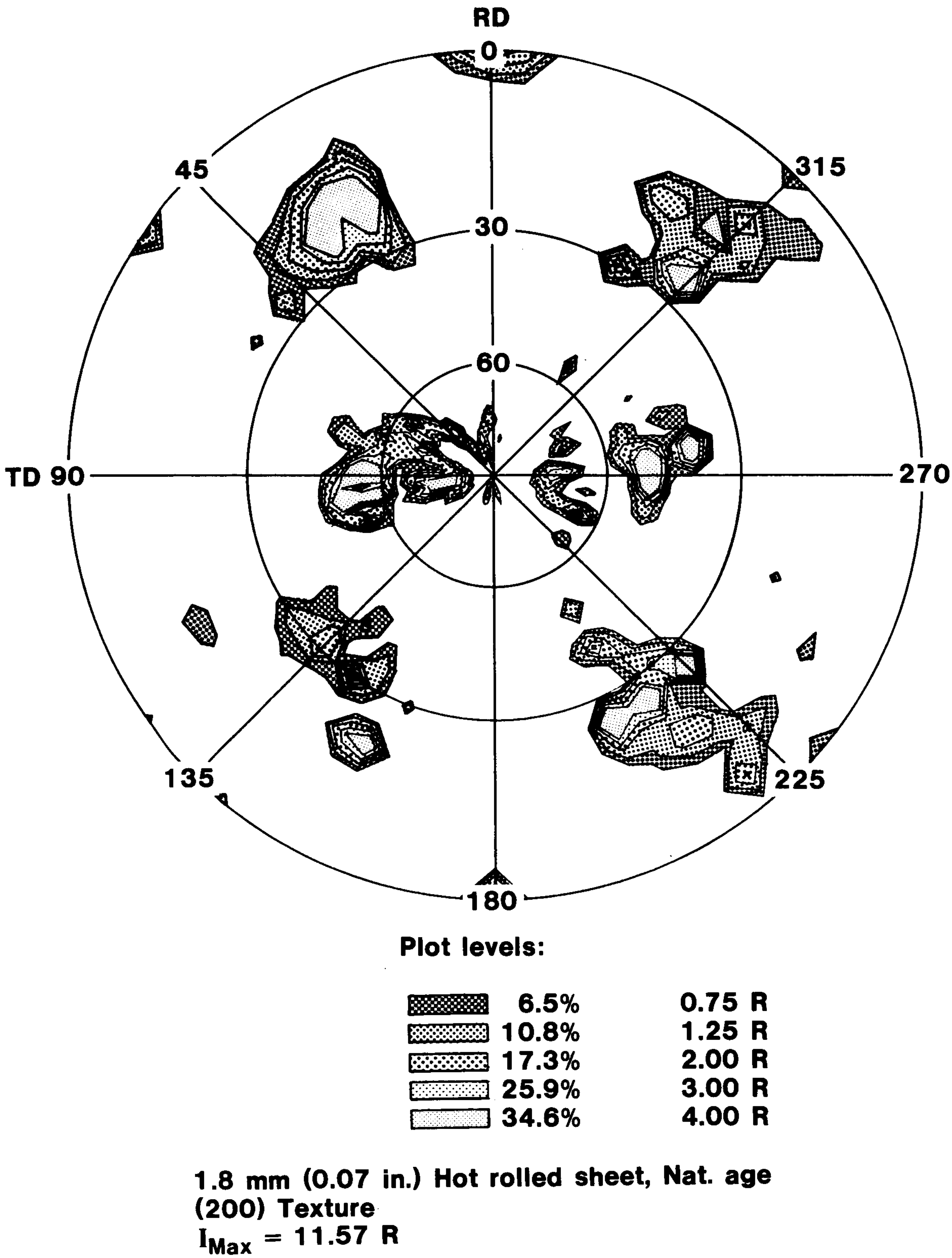


Figure 31. - {200} x-ray pole figure of PM hot rolled sheet variant at T/2 position, solution heat treated temper.

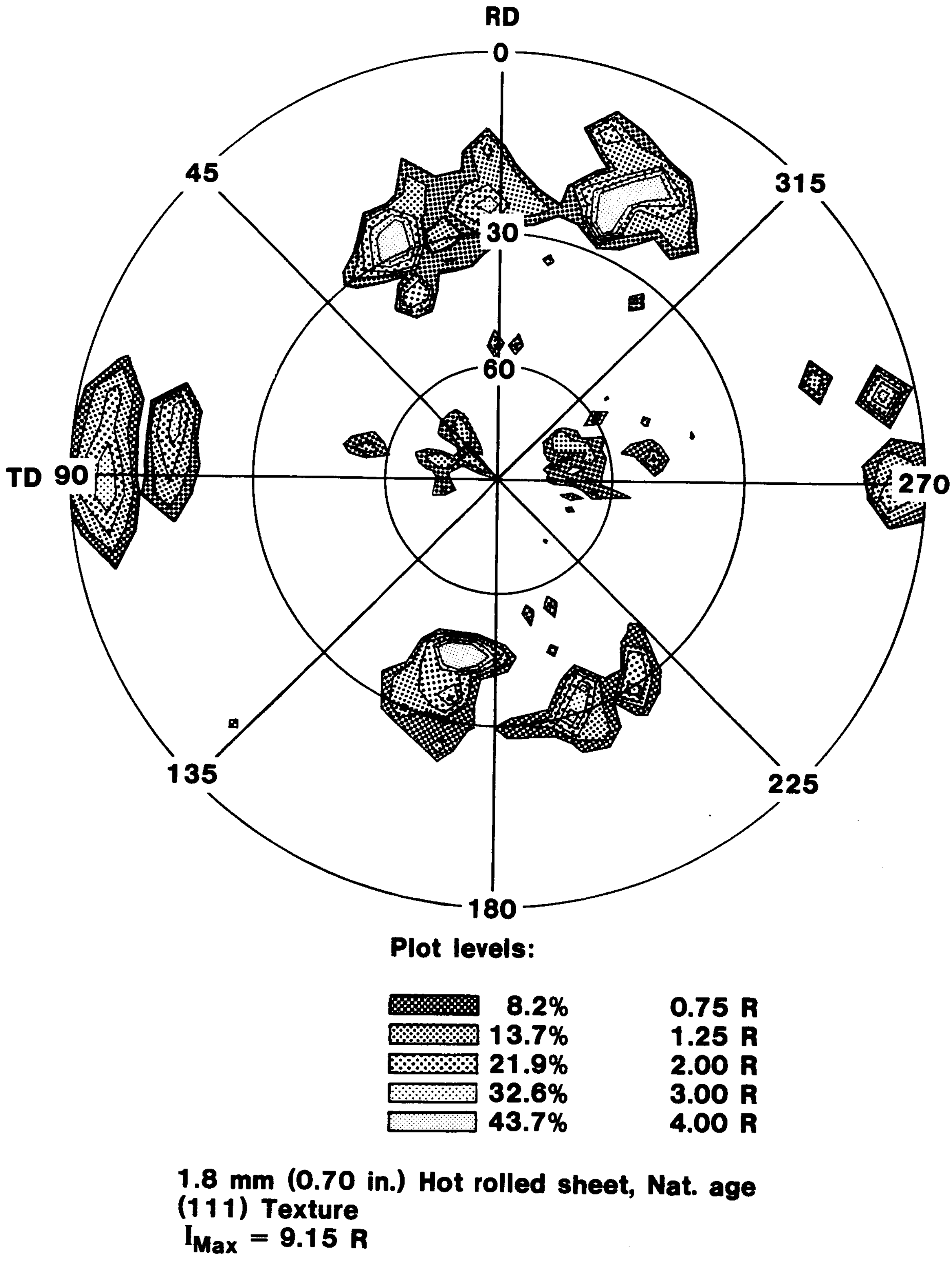


Figure 32. - {111} x-ray pole figure of PM hot rolled sheet variant at T/2 position, solution heat treated temper.

variants recrystallized on solution treatment, but developed distinctly different textures. The total strength of the textures was relatively low, indicating that a high degree of random orientations occurred during recrystallization.

4. DISCUSSION

The present study has demonstrated that PM 2XXX Al alloys can be produced in thin plate and sheet gages with substantially improved tensile strength and fracture toughness properties compared to IM Al alloys. A comparison of tensile strength variations with product thickness in Figure 33 serves to illustrate the magnitude of the improvements. The figure shows the variation in yield and tensile strength of several new IM 2XXX Al alloys in comparison with the identical properties for PM 2XXX Al extrusions, plate, and sheet from the current investigation. While both IM and PM 2XXX Al alloys exhibited a decrease in strength with thin material gages, the PM alloys possess a dramatically higher yield strength in these thin gage sections. The superior behavior of the PM 2XXX Al alloys is attributed to the enhanced ability of PM alloys to inhibit recrystallization and grain growth during various processing histories. The yield strength of the 0.070 in. thick sheet is approximately 25 pct. higher than a IM 2034-T351 control alloy, a Zr modified version of IM 2024 Al. The advantage in tensile strength of the PM Al materials is marginal in the thin gages, and results in only about a 5 pct. improvement at 0.75 in. thickness. The similarity in tensile strength properties is probably a reflection of the work hardening characteristics associated with the strengthening precipitates. Data given in the tables indicate that substantial hardening can be obtained in the PM Al sheet forms despite the initially lower yield strength levels. The PM 2XXX Al products have also shown comparable yield and tensile strengths as a function of longitudinal and transverse directions.

Complementary to the improved yield strength properties of the PM Al alloys, there is a substantial improvement in the fracture toughness levels. In general, the PM 2XXX Al alloy materials offer a much better combination of strength and toughness compared to equivalent IM Al alloys. The attempts to evaluate the influence of grain structure on property behavior through the use of two processing variants have demonstrated that a better combination of strength and toughness is available in plate gages with warm rolled processing conditions. However, the data do not show a conclusive benefit of one processing variant over the other on the basis of strength-toughness at thinner sheet gages. The texture analysis has established that the crystallographic textures are similar in the plates gages which probably explains the relatively mild response of strength-toughness combinations to changes in processing history.

The hot rolled variant contributed to better longitudinal properties on isothermal aging at either of the two temperatures. Additionally, the hot rolled variant attained higher strength levels and maintained them for longer

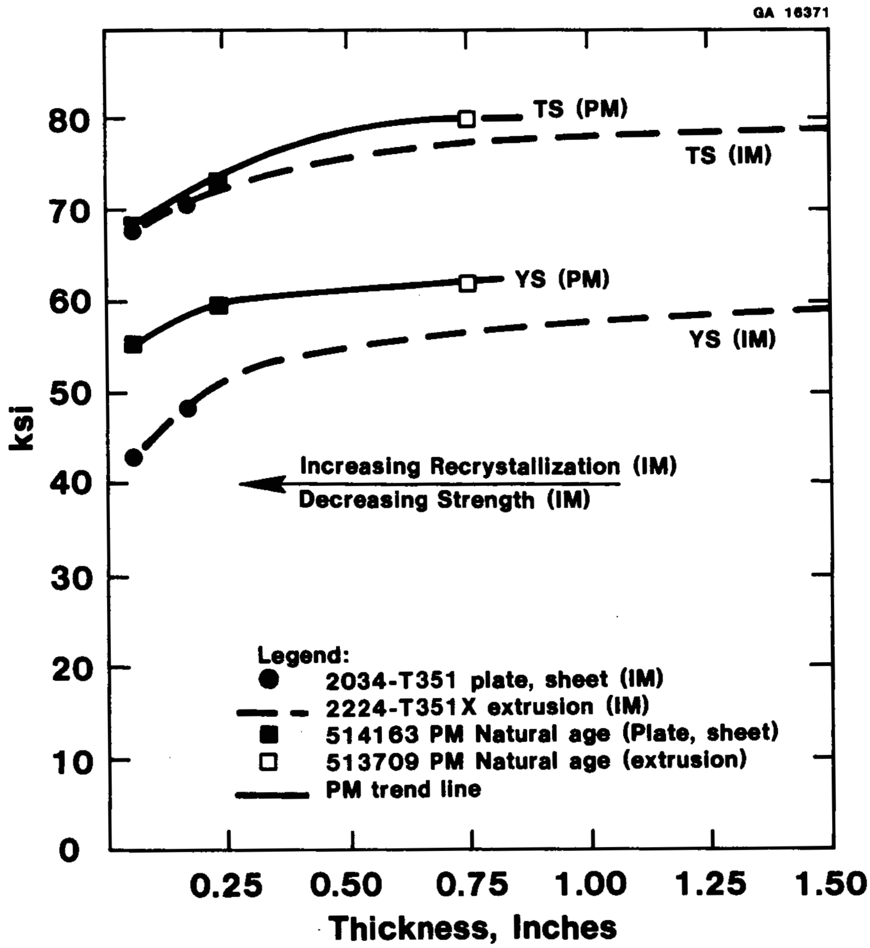


Figure 33. - Comparison of tensile and yield strength variation with product thickness of PM 2XXX and IM 2XXX Al alloys.

periods of time. Although the corrosion performance has not been evaluated to date, it may be advantageous to select a processing history that allows more flexibility in aging to achieve adequate resistance to stress corrosion cracking and intergranular corrosion. The peak strengths of the PM plate in the transverse direction were similar at both aging temperatures.

The hot rolled sheet material displayed better tensile strength properties than the warm rolled variant in both the longitudinal and transverse orientations. The L-T tear strength/yield strength ratio performance of the two processing conditions indicated a common behavior, although there was more scatter associated with some of the overaged tempers. On the other hand, the T-L tear strength results were similar for both processing variants. When the strength - toughness combination is assessed by unit propogation energy measurements, the warm rolled sheet appears to show higher L-T toughness values, but the hot rolled sheet condition demonstrated better T-L toughness levels. If the scatter in the test methods is considered, the performance of the two processing variants is judged to be identical. This behavior was observed despite significant differences in the inherent crystallographic textures of the PM sheet materials.

Previous work on IM and PM Al alloy fatigue crack growth behavior has demonstrated that a complex interaction exists between grain structure, loading mode, and loading amplitude in retardation of crack growth. These studies have indicated that a coarser grain structure in PM alloys can cause a larger contribution to crack closure effects dependent on the characteristics of the loading amplitude. The current work suggests that the fatigue crack growth characteristics are likely to be different as a consequence of the coarse and duplex grain structures in plate and sheet material forms. The fatigue crack growth behavior can be contrasted to the results obtained on PM 2XXX Al extrusions where the grain structure is fine and uniform in distribution.

5. CONCLUSIONS

The present study on PM 2XXX Al alloy plate and sheet materials has demonstrated the following:

1. PM 2XXX Al alloys can be produced in plate and sheet material forms with outstanding strength and fracture toughness improvements over IM Al alloys.

2. PM 2XXX Al alloys show a significant advantage in yield strength properties compared to equivalent IM Al alloys in thin plate and sheet gages.

3. Due to the presence of both Al_3Zr and oxide phases, the PM Al alloy materials are unusually more resistant to recrystallization processes (or concomitantly, a greater insensitivity to variations in processing history) than IM Al alloys.

4. Although recrystallization does occur in thinner gages of some PM Al alloy materials, aging treatments are effective in providing attractive property behaviors.

6. RECOMMENDATIONS FOR FUTURE WORK

The results of the current investigation on PM 2XXX Al alloy plate and sheet materials leads to the following recommendations:

1. The smooth and notched fatigue behavior of these PM 2XXX Al alloy plate and sheet materials should be evaluated for promising aging tempers.

2. The stress corrosion and general corrosion performance of these PM 2XXX Al alloy materials should be established for appropriate combinations of aging temperature and time.

3. The fatigue crack growth behavior in variable and constant amplitude loading histories should be determined for the PM 2XXX Al alloy plate and sheet materials. This evaluation will assess the ability of various PM 2XXX Al alloy products to maintain adequate strength, toughness, and fatigue performance as a function of grain size and morphology.

4. The strength and fracture toughness performance of these PM 2124 Al plate and sheet gage materials should be evaluated and verified in a prototype flat rolled product development program.

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16. Abstract
The objective of the present investigation is to fabricate and evaluate PM 2124 Al alloy plate and sheet materials in accordance with NASA program goals for damage tolerance and fatigue resistance. Previous research has indicated the outstanding strength-toughness relationship available with PM 2124 Al-Zr modified alloy compositions in extruded product forms. The range of processing conditions was explored in the fabrication of plate and sheet gage materials, as well as the resultant mechanical and metallurgical properties. The PM composition based on Al-3.70 Cu-1.85 Mg-0.20 Mn with 0.60 wt. pct. Zr was selected for investigation. Flat rolled material consisting of 0.250 in. thick plate and 0.070 in. thick sheet was fabricated using selected thermal mechanical treatments (TMT). The schedule of TMT operations was designed to yield the extreme conditions of grain structure normally encountered in the fabrication of flat rolled products, specifically recrystallized and unrecrystallized. The PM Al alloy plate and sheet materials exhibited improved strength properties at thin gages compared to IM Al alloys, as a consequence of their enhanced ability to inhibit recrystallization and grain growth. In addition, the PM 2124 Al alloys offer much better combinations of strength and toughness over equivalent IM Al. The alloy microstructures were examined by optical metallography and crystallographic texture techniques in order to establish the metallurgical basis for these significant property improvements.

17. Key Words (Suggested by Author(s))
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2124 Al Alloys
Sheet
Damage Tolerance and Fatigue Resistance
High Temperature
Warm Rolling
Fracture Toughness
Hot Rolling

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